




Revised Report

Performance Evaluation of Phase II In Situ Enhanced Anaerobic Bioremediation Treatability Study


Signetics Site

Sunnyvale, California


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Protection Agency, Region 9


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List of Acronyms and Abbreviations

ACRONYM	DESCRIPTION
1,1-DCE	1,1-Dichloroethene
ASAOC	Administrative Settlement Agreement and Order on Consent
bgs	Below Ground Surface
CA	California
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
cis-DCE	cis-1,2-Dichloroethene
CO ₂	Carbon Dioxide
COC	Chemical of Concern
DHC	Dehalococcoides
DNAPL	Dense Non-Aqueous Phase Liquid
DO	Dissolved Oxygen
DQO	Data Quality Objectives
DTSC	Department of Toxic Substances Control
DUP	Duplicate Sample
EAB	Enhanced Anaerobic Bioremediation
EPA	United States Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program

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ACRONYM	DESCRIPTION
EVO	Emulsified Vegetable Oil
Freon 113	1,1,2-trichlorotrifluoroethane; CFC 113
ft/day	Feet per Day
GAC	Granular Activated Carbon
gpm	Gallons per Minute
HASP	Site-Specific Health and Safety Plan
HLA	Harding Lawson Associates
in. H ₂ O	Inches of Water Column
In. Hg	Inches of Mercury
LEL	Lower Explosive Limit
MCL	Maximum Contaminant Level
µg/L	Micrograms per Liter
µm/s	Micrometers per Second
mg/L	Milligrams per Liter
mL/min	Milliliters per Minute
nM	nanoMolars (nmol/L)
NPDES	National Pollutant Discharge Elimination System
ORP	Oxidation-Reduction Potential

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ACRONYM	DESCRIPTION
PAIP	Pressure Activated Injection Probe
PCE	Tetrachloroethene
ppm	Parts per Million
PSI	Pounds per Square Inch
QA/QC	Quality Assurance/Quality Control
QAPP	Quality Assurance Project Plan
RD/RA	Remedial Design/Remedial Action
REG	Regular (primary) sample
ROD	Record of Decision
ROI	Radius of Influence
RWQCB	Regional Water Quality Control Board
SRS-SD	Slow Release Substrate (SRS®) Small Droplet Emulsified Vegetable Oil Substrate
SOP	Standard Operating Procedure
SVE	Soil Vapor Extraction
TCE	Trichloroethene
TDIP	Top-down Injection Probe
TOC	Total Organic Carbon
TSI-DC	Terra Systems Inc. <i>Dehalococcoides mccartyi</i> Bioaugmentation Culture®

ACRONYM	DESCRIPTION
UEL	Upper Explosive Limit
VOC	Volatile Organic Compound

1 Introduction

This report provides an evaluation of the in situ enhanced anaerobic bioremediation (EAB) Phase II treatability study conducted at the former Signetics facility in Sunnyvale, CA (Site) for the period of September 2020 through November 2021. This evaluation report was prepared in accordance with the EPA-approved *Phase II Enhanced Anaerobic Bioremediation (EAB) Treatability Study Work Plan* (Locus Technologies, 2020) (Work Plan) dated 23 June 2020.

This report and its appendices demonstrate that post-injection monitoring field activities and data evaluations were conducted as outlined in the Work Plan. Field activities conducted in support of the injection time frame were documented in the *Injection Completion Report, Enhanced Anaerobic Bioremediation (EAB) Phase II Treatability Study* (Locus Technologies, 2021) (Injection Completion Report) dated 4 January 2021.

The Phase II treatability study goal is to complement and enhance the findings and recommendations presented in the EAB Study (Phase I) performed from November 2016 through December 2017. The overall objective of the treatability study is to evaluate the effectiveness of in situ enhanced anaerobic bioremediation of volatile organic compounds (VOCs) within the “A” aquifer at or near the Site source area for the enhancement of reductive dechlorination of chlorinated ethenes, specifically trichloroethene (TCE), as a potential treatment technology.

This evaluation report was prepared by Locus Technologies in response to the Administrative Settlement Agreement and Order on Consent (ASAOC) for the Site. The settlement was entered into voluntarily by Philips Semiconductors, Inc. (Philips) and the United States Environmental Protection Agency (EPA) with an effective date of 15 March 2019.

1.1 Site Background

The Site is located in Sunnyvale, California and is comprised of four contiguous parcels: two former semiconductor fabrication and testing facilities located at 811 East Arques Avenue (811

Arques) and 440 North Wolfe Road (440 Wolfe), as presented in Figure 1, and two office buildings located at 815 and 830 Stewart Drive. The properties are no longer owned or operated by Philips. Past investigations at the Site have determined that groundwater is impacted with VOCs.

Chemicals of concern (COC) for the Site were established in the California Regional Water Quality Control Board (RWQCB) Order 91-104 (Order), adopted on 19 June 1999. Two additional chemicals were added in February 2020 by the EPA. The ten current chemicals of concern for this study are:

Chemicals of concern
Chloroform
1,1-dichloroethane (1,1 - DCA)
1,1-dichloroethene (1,1-DCE)
<i>cis</i> -1,2-dichloroethene (<i>cis</i> -DCE)
<i>trans</i> -1,2-dichloroethene (<i>trans</i> -DCE),
tetrachloroethene (PCE)
1,1,2-trichloro-1,2,2-trifluoroethane (Freon 113)
1,1,1-trichloroethane (1,1,1-TCA)
trichloroethene (TCE)
vinyl chloride

The principal constituent of concern is TCE, which, along with its daughter compounds, has been the focus of the Phase II study. Cleanup standards for these COCs were established in the 1991 *EPA Superfund Record of Decision* (ROD) (EPA, Environmental Protection Agency (EPA), Superfund Record of Decision: Signetics (Advanced Micro Devices 901)(TRW Microwave), First Remedial Action –Final, September, EPA/ROD/R09–91/074, 1991).

1.2 Site Hydrogeology

The aquifer system at the Site has been described in detail in the *Remedial Investigation Report* [Harding Lawson Associates (HLA) et al., 1991]. The subsurface has been divided into the "A" and "B" aquifer zones. The aquifers occur at the approximate depths listed in Table 1 and below.

Aquifer	Approximate Depth Below Ground Surface (bgs)
"A"	10 – 30
"B1"	30 – 50
"B2"	50 – 70
"B3"	70 – 90

Previous investigations at the Site have revealed that the aquifers have varying thicknesses and are frequently discontinuous. At some locations, more than one water-bearing unit may be present within an aquifer. There are also localized areas where aquifers coalesce. The "A" aquifer is generally more laterally continuous at the Site than the other aquifers (Emcon, 1984) (EMCON,

1996) and characterized by silty and clayey sand with thin, localized sandy and gravelly channel deposits. Boring logs of established monitoring and extraction wells within the treatment area in the "A" aquifer are presented in Appendix A of the Work Plan. Boring logs of the three new wells installed as part of the Phase II EAB ~~W~~work Plan implementation are presented in Appendix A of the Injection Completion Report.

In 2005, excavated clean soil from the demolition of the 811 Arques facility was placed in the current bioremediation study area. This soil has created a mound of fill that is approximately six to nine feet (ft) above the grade of the remainder of the site. Thus, the aquifer depths in the bioremediation study area are approximately six to nine feet deeper than the values in the table above.

Regional groundwater flow in the "A" aquifer is generally northward at the Site. However, operating extraction wells, trenches, and sumps cause the groundwater flow direction to differ from this in the vicinity of the Site, as noted in the treatability study area where it flows ~~north east~~northeast. "A" aquifer groundwater elevation contours for 2020 are presented in the *Annual Groundwater Report* (Locus Technologies, 2021) and have been integrated in Figure 2.

2 Purpose

The overall objective of the treatability study is to evaluate the effectiveness of in situ enhanced anaerobic bioremediation (EAB) of VOCs within the "A" aquifer at or near the site source area for the enhancement of reductive dechlorination of chlorinated ethenes as a remedial technology. A list of objectives was developed in Section 4.1 of the Work Plan (Locus Technologies, 2020) and are presented below.

- ◇ Improve the monitoring network by adding three additional monitoring wells in the treatability study area for baseline and progress monitoring; one additional well at the

upgradient end of the treatability study area, and two additional wells at the downgradient end of the treatability study area.

- ◇ Collect injection pressure data at varying flow rates to refine injection procedures for future full-scale implementation.
- ◇ Gauge water levels surrounding injection points to measure the radius of influence (ROI) of the injection.
- ◇ Increase carbon availability across the study area to decrease electron acceptor profile, mitigate VOC rebounds, and support the repopulation of inoculated microbial cultures.
- ◇ Increase *Dehalococcoides* (DHC) populations where populations have declined below the target of 1×10^6 cells/L (1×10^3 cells/mL) based on third quarter monitoring: S146A and S140A.
- ◇ Implement a gridded injection, expanding reactive zone to reduce the effects of boundary conditions (the effects of untreated areas on treated areas) and migration of VOCs to downgradient areas.
- ◇ Implement a gridded injection based on a 20-foot ROI, verified with field observations such as water levels or appearance.
- ◇ Determine the effectiveness of Slow Release Substrate (SRS®)– Small Droplet Emulsified Vegetable Oil Substrate (SRS-SD) and Terra Systems Inc. *Dehalococcoides mccartyi* Bioaugmentation Culture® (TSI-DC) bioaugmentation culture is effective at promoting anaerobic degradation of chlorinated ethenes and Freon-113 at S140A and S141A.
- ◇ Refine in situ remedial parameters for full-scale implementation.
- ◇ To demonstrate that injection of this substrate would not create unintended adverse impacts to groundwater.

The EAB system has been evaluated for effectiveness based on performance monitoring data collected over a period of twelve months. Per Section 4.6 of the Work Plan, evaluation of data is intended to determine:

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- ◇ whether the data passed data quality criteria,
- ◇ whether SRS-SD created a reducing geochemical environment and its co-application with TSI-DC induce biotic and abiotic anaerobic degradation of TCE to below baseline concentrations; and if so,
- ◇ optimal in situ parameters (such as substrate volumes, injection rates, number of applications, effective ROI) for use in developing a full-scale EAB program to remediate the impacted groundwater.
- ◇ Additionally, the data will inform the rate of formation and degradation of biodegradation daughter products and formation of non-toxic byproducts ethene and ethane.

Performance monitoring parameters to support the above objectives and determinations were developed in the Work Plan and evaluated based on performance expectations. Descriptions of specific parameters and how they are intended to be used and interpreted are shown in Table 3 and Table 7 of the Work Plan.

3 Summary of Field Activities

The following section summarizes Phase II EAB related activities at the Signetics site. The EAB injections were conducted in November 2020 followed by post-injection performance monitoring activities for one-year. A complete discussion of the injection field activities can be found in the Injection Completion Report (Locus Technologies, 2021).

Prior to the start of injections, a baseline groundwater monitoring event was conducted at the Site from 14–16 September 2020 to gather data necessary for assessing potential COC rebounding in the area of the Phase I injections and ultimately, for adjusting the substrate injection volumes and concentrations based on COC and geochemical conditions at the time of injections. To improve the monitoring network, three additional monitoring wells were installed via hollow stem auger on 3–4 September 2020: S158A, S159A, and S160A. These three A-aquifer wells were installed to provide supplemental information on the lateral extent of the injection

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ROIs as well as baseline groundwater conditions. S159A and S160A are located on the north end of the Phase II study area and one well S158A is located on the south end (see Figure 1). Using the results from the baseline monitoring event, substrate volume requirements originally proposed in the Work Plan were recalculated using the Environmental Security Technology Certification Program (ESTCP) Substrate Calculation Tool developed by Parsons (Parsons, 2010). Volumes were then adjusted for the SRS–SD substrate demand that requires a minimum of 500 milligrams/liter (mg/L) total organic carbon (TOC) (Locus Technologies, 2021). These design volumes were then further increased by approximately 50% at all injection locations to account for elevated sulfate concentrations. At two injection points, the SRS–SD and injection solution volumes were further increased, by 250% and 50%, respectively. Final injection quantities were documented by Cascade and discussed below.

3.1 Injection Implementation

A bioremediation injection solution consisting of emulsified vegetable oil (EVO), bioaugmentation culture, conditioned water, and sodium bicarbonate was injected into the subsurface soils and groundwater in the Phase II treatability study area (Figure 2). The EVO product implemented in this study was SRS–SD substrate and the bioaugmentation culture was TSI–DC.

After EPA–approval the Work plan~~Plan~~Workplan, field staff mobilized and began the pre–injection process. This started on 5 November 2020 with the conditioning of injection water to create an optimal anaerobic environment for the bacteria. To accomplish this, water was treated with sodium ascorbate in two 21,000–gallon water tanks and monitored periodically for decreasing dissolved oxygen (DO) and oxidation–reduction potential (ORP) values. The ideal target for the conditioned injection water was dissolved oxygen (DO) of 0.5 mg/L and a negative oxidation–reduction potential (ORP). Although the DO concentration was slightly above the target, based on the negative ORP and the asymptotic response to additional sodium ascorbate, it was determined that the conditioned injection water reached satisfactory levels of DO and ORP (0.92 mg/L and –

147.7 ORP, respectively) on 10 November 2020. During onsite discussions with the substrate vendor and EPA, the consensus was that the DO was sufficiently low to proceed. The remainder of the injection solution was then mixed in tanks located on the injection platform. The injection solution consisted of SRS-SD substrate, conditioned water, sodium bicarbonate, and TSI-DC bioaugmentation culture in the quantities detailed in Table 1.

From 10–20 November 2020, ~~ten~~ twelve injections were conducted with a track-mounted direct push drill rig equipped with an injection platform. The first 5 feet of each injection borehole was advanced via hand auger to ensure underground utility clearance. The injection solution was prepared in a two-step process: SRS-SD, conditioned water, and sodium bicarbonate was first mixed in tanks located on the injection platform, then the TSI-DC culture was injected inline as the mixture was pumped to the drill rig at each injection location. The solution was injected via two methods (see Section 4.3.1), with injections administered every 2.5 feet for eight intervals, amounting in a total of 20 feet of injected substrate mixture at each location. Injections proceeded in the order seen in Table 1 at the locations seen in Figure 2. The following changes from the ~~work~~ Work Plan design were noted:

- ◇ The highest SRS-SD concentration was injected at INJ-5 instead of the target INJ-1 because it was closer to the area of higher baseline TCE concentrations.
- ◇ At the last injection location, INJ-6, the SRS-SD concentration was increased to 140 gallons to use up remaining substrate conditioned water.
- ◇ The 150% dilution volume was ultimately injected at INJ-9 instead of the target INJ-12 because it was closer to higher baseline TCE concentration where an increased ROI could be beneficial.
- ◇ The initial injection depth was approximately 15 ft bgs, which was 5 ft deeper than the 10 ft bgs Work Plan specified depth. This was due to the presence of additional fill above grade as discussed in the Completion Report. The ending depth was also subsequently



lower, at 35 ft bgs. When considering the fill, the aquitard depth is 36–39 ft bgs, therefore aquitard penetration is unlikely. The borehole was also grouted.

The contractor logged flow rates, pressures, and amendment ratios. Locus monitored back pressures and the visual presence of daylighting for each injection interval. Daylighting did not occur during the introduction of the materials. Injection delivery and monitoring field logs are included in Appendix A.

During injection activities, water levels were gauged simultaneously with well-dedicated sounders at well locations nearest to the concurrent injection point as another means to monitor potential daylighting. Groundwater elevations fluctuated at time of injections, indicating that injection point was hydrologically connected to the treatability area. Injection period groundwater levels are included in the Appendix A daily field activity logs and the plots seen in Appendix B. Monitoring wells in the Phase II study area were also sampled during the injection activities to assess the distribution of the substrate. Field parameters and laboratory results can be seen in Table 2 and Table 3, respectively.

Additionally, on the last day of injections, 20 November 2020, three borings (TW-1, TW-2, and TW-3) were advanced via direct push to roughly 13 ft-bgs to collect grab groundwater samples. These ad hoc samples were intended to bolster constraints on the baseline lateral extent of VOCs in the Phase II study area. Upon complete delivery of substrate at each injection point and the collection of grab samples at the exploratory borings, each boring was grouted with Portland cement and covered with native soil to restore each original surface. Upon complete delivery of substrate at each injection point, borings were grouted and covered with native soil. The area of activity was ~~decommissioned~~decommissioned, and waste removed within 24 hours following the last injection.

3.2 Post-Injection Monitoring

The Phase II study area was monitored post-injections to gather data for this performance evaluation. The post-injection data gathering process consisted of 1) sampling and monitoring groundwater from fourteen existing monitoring wells (S025A, S049A, S088A, S134A, S137A, S138A, S139A, S140A, S141A, S143A, S146A, S1598A, S159A, and S160A) (Figure 2) and 2) collection of vapor soil gas samples downgradient from treatability area (Figure 3) to ensure methane produced by the bioremediation process was not a hazard to nearby buildings and receptors. Field monitoring and sampling logs from each groundwater sampling event are included in Appendix C. Soil vapor well construction logs are included in Appendix C of the Phase I Evaluation Report (Locus Technologies, 2018), and sampling logs are shown in Appendix DE.

The series of field events conducted for post-injection monitoring were as follows:

- ◇ Month 1 Groundwater Monitoring: 15–18 December 2020
- ◇ Month 2 Groundwater Monitoring: 18–20 January 2021
- ◇ Month 3 Groundwater Monitoring: 15–17 February 2021
- ◇ Methane Soil Vapor Monitoring: 18–19 February 2021
- ◇ Methane Soil Vapor Monitoring: 17 March 2021
- ◇ Methane Soil Vapor Monitoring: 16 April 2021
- ◇ Quarter 2 Groundwater Monitoring: 17–19 May 2021
- ◇ Methane Soil Vapor Monitoring: 21 May 2021
- ◇ Methane Soil Vapor Monitoring: 21 June 2021
- ◇ Methane Soil Vapor Monitoring: 17 July 2021
- ◇ Methane Soil Vapor Monitoring Re-sample: 6 August 2021
- ◇ Quarter 3 Groundwater Monitoring: 17–19 August 2021
- ◇ Quarter 4 Groundwater Monitoring: 8–10 November 2021

3.2.1 Groundwater Monitoring

In order to validate the effectiveness of the EAB design following the injections, a groundwater monitoring plan was developed, which is outlined in Table 2 of the Work Plan for the Phase II Treatability Study (Locus Technologies, 2020). The monitoring plan was designed to provide sufficient data to evaluate the effectiveness of the study and to provide the necessary information to plan a full-scale implementation of the technology if the treatability study is successful.

3.2.1.1 Groundwater Sampling Procedures

Post-injection performance monitoring was conducted monthly for the first three months following the injection event, then quarterly for three additional sampling events. At each well, concentrations of off-gassed methane trapped within the well-headspace was measured and recorded with a RKI Eagle 2 portable gas detector. Water levels were gauged using an electronic water level indicator graduated to 0.01 feet, and then referenced to the top of the well casing elevation. Groundwater samples were collected using low flow purging and sampling methods described in the EPA's EQASOP-GW4 Standard Operating Procedure (SOP). At the time of purging, Hach field tests were used to gather arsenic, ferrous iron, and manganese groundwater samples at the well head to protect samples from exposure to oxygen. Post-injection monitoring field parameter results are compiled in Table 4.

Dedicated sample tubing was utilized at each well to lower the possibility of cross contamination. Equipment that was used at more than one sample location, however, was decontaminated prior to sampling a subsequent well using a standard 3-stage decontamination process.

3.2.1.2 Groundwater Analyses

Table 5 outlines the complete post-injection groundwater monitoring analysis schedule. Samples were analyzed for the following analytes using the test methods below, as established in the Work Plan (Locus Technologies, 2020):

- ◇ Alkalinity (SM 2320)
- ◇ Carbon Dioxide (RSK 175)
- ◇ Dehalococcoides (DHC)(QuantArray-chlor)
- ◇ Hydrogen (AM20GAX)
- ◇ Manganese and Arsenic, Dissolved (EPA 200.7)
- ◇ Methane, Ethane, and Ethene (RSK 175)
- ◇ Nitrate and Sulfate (EPA 300.0)
- ◇ Sulfide (SM 4500)
- ◇ Total Organic Content (SM 5310C)
- ◇ Volatile Fatty Acids (AM23G)
- ◇ Volatile Organic Compounds (EPA 8620B)

Groundwater samples were submitted to Eurofins/Test America, Pleasanton, CA for all laboratory analyses, except for dissolved gases (RSK 175), metabolic acids (AM23G), hydrogen (AM20GAX), and DHC (QuantArray-chlor) analyses. Samples for the former three analyses were submitted to Pace Analytical in Baton Rouge, LA. DHC analyses were submitted to Microbial Insights, Inc. of Rockford, TN. All laboratories adhered to industry-standard QA/QC procedures when completing analyses. Post-injection monitoring laboratory results are compiled in Table 6 and laboratory results are in Appendix D.

3.2.1.3 Groundwater QA/QC Samples

Sampling was performed according to test method procedures and the appropriate Quality Assurance/Quality Control (QA/QC) measures, all of which are established in the *Quality Assurance Project Plan (QAPP) for Enhanced Anaerobic Bioremediation Treatability Study – Phase II* (Locus Technologies, 2020). This included collecting one field blank sample per each event to verify sample integrity during sample collection procedures. Similarly, one set of trip blank samples were sent to the lab with the regular field samples on each sampling day. Trip blank

samples were analyzed for VOCs to ensure that any compounds detected in the sample were not the result of contamination during the handling and sampling process used for the samples prior to analysis. Lastly, one field duplicate sample was collected per each sampling event using laboratory-certified blank water. Results of the QA/QC samples are discussed in Section 4.14.

3.2.2 Soil Vapor Monitoring

3.2.2.1 Methane Monitoring Criteria

While increased methane concentrations in groundwater and well-head vapor would most likely indicate favorable subsurface conditions for anaerobic biological activity, excessive methane concentrations could potentially pose both a fire hazard and a hazard to field personnel and nearby other receptors. Specifically, methane is explosive when present in concentrations between its lower explosive limit (LEL) of 50,000 parts per million (ppm) and its upper explosive limit (UEL) of 150,000 ppm (NIOSH, 2007). In the QAPP, specific methane concentration criteria for both groundwater and well-head vapor were identified that correspond to an action or set of actions. The primary response to elevated methane concentrations in well-head vapor and groundwater is to continue monitoring methane at the frequency of groundwater sampling. However, when well-head methane concentrations exceeded 10% of its LEL (5,000 ppm) and methane in groundwater exceeds 10 mg/L in the same well, the QAPP states that soil vapor would be sampled at three previously installed dual-nested soil vapor implants placed adjacent to the surrounding commercial buildings (Figure 3). The action criteria from the QAPP are outlined in the table below.

Methane Concentration Criteria	Action
<p><10% LEL (5,000 ppm) in well-head vapor</p> <p>AND</p> <p>>10 mg/L in groundwater</p>	<ul style="list-style-type: none"> Continue monitoring well-head vapor at the frequency of groundwater sampling or higher (i.e. monthly or biweekly) depending on groundwater (IDEM, 2019).
<p>>10% LEL (5,000 ppm) in well-head vapor</p> <p>AND</p> <p>>10 mg/L in groundwater</p>	<ul style="list-style-type: none"> Soil gas monitoring points near receptors shall be sampled Continue monitoring well-head vapor at the frequency of groundwater sampling or higher (i.e. monthly or biweekly) depending on groundwater and well-head results (IDEM, 2019).
<p>>25% LEL (12,500 ppm) in well-head vapor</p> <p>AND</p> <p>>10 mg/L in groundwater</p>	<ul style="list-style-type: none"> When above ground structures, preferential pathways and subsurface structures are not present, venting would usually be an appropriate mitigation measure unless concentrations are extremely high site-wide (IDEM, 2019). Continue monitoring at a monthly frequency or higher, depending on well-head results.

3.2.2.2 Criteria Exceedances

During the second and third monthly (18–20 January 2021 and 15–17 February 2021, respectively) groundwater sampling event, wells S137A and 139A both recorded well-head methane vapor concentrations exceeding 5,000 ppm and methane concentrations in groundwater greater than 10 mg/l. In response, ~~monthly~~response, monthly samples were collected from the vapor wells between February and August 2021, until the action triggering criteria were no longer met.

3.2.2.3 Soil Vapor Sampling Procedures

Soil vapor sampling equipment and procedures were selected in accordance with the 2015 California Department of Toxic Substances Control (DTSC) and RWQCB Advisory Active Soil Gas Investigations guidance (DTSC, 2015).

3.2.2.4 Shut-In Test

Prior to sampling each soil vapor well, a quantitative shut-in test was conducted on each new sample train. The shut-in test involved applying a minimum vacuum of 100 inches of water column (In. H₂O) to the sample train with a vacuum pump to evacuate the lines. A shut-off valve to the vacuum pump was then closed and the sample train remained under vacuum for approximately five minutes to assess whether there was any loss of vacuum. If there was any observable loss of vacuum, the fittings on the sample train were then adjusted until the vacuum in the sample train did not noticeably dissipate. If the sample manifold would not hold vacuum after this adjustment, the sample manifold was discarded for a new one. After the shut-in test was successfully completed, the result was recorded on field sampling forms and the sampling train was not altered until the sample was collected. The field forms for soil vapor sampling events are included in Appendix E.

3.2.2.5 Sample Collection

Each vapor point was purged 3 case volumes using a vacuum pump, regulated to a flow rate of 150 milliliters per minute (mL/min). A new flow regulator was used for the collection of each new sample to avoid cross contamination. Purge volumes were calculated using standard methods that account for the borehole diameter, well construction material porosity, and the tubing diameter and length. Both purging and sampling occurred within a tracer gas shroud held to an ambient concentration of at least 10 percent helium to check for communication between the surface air and vapors at depth. Both in-line helium and ambient helium in the shroud were measured using standard helium gas detectors. At regular intervals during purge and sample

collection, in-line helium and shroud helium concentrations in addition to well-side and canister vacuum pressures were recorded (Appendix E).

After purging, all samples were collected into passivated 1.4-liter stainless steel Summa canisters at the same flow rate of 150 mL/min. Once the canister vacuum gauges reached between 5 and 2 inches of mercury (In. Hg), the sample was collected, and the canister valve was closed. The canister's final vacuum reading was noted on field sampling forms and on the chain-of-custody to document sample integrity (Appendix E). Additionally, methane was measured and recorded with a RKI Eagle 2 portable gas detector at each soil vapor well where a sample was collected.

3.2.2.6 Soil Vapor QA/QC Samples

At least one co-located duplicate sample was collected during each sampling day. The replicate samples were intended to evaluate analytical variability between samples. These field duplicate samples were obtained over the same time interval as the original sample and were sampled according to the same procedures previously described. Additionally, at least one field blank sample was obtained during each sampling day, using pure nitrogen gas as the blank gas. The field blank results were intended to verify sample integrity during the process of field sample collection.

The soil vapor samples were delivered directly to the laboratory following field activities. All samples were analyzed for methane and helium using method ASTM D-1946 for fixed gases. Sample analysis was conducted by Enthalpy Analytical in Orange, CA.

3.3 Deviations

The following were notable deviations from the activities described in the EAB Phase II Work Plan:

- ◇ During the Month 1 event, samples were not analyzed for arsenic and manganese by EPA 200.7. —During these events, arsenic and manganese were measured using field measurement HACH kits. The 2020 Work PplanWorkplan specifies that either the field kits

or EPA 200.7 analysis may be used for determining concentrations of these metals. In subsequent events, lab analysis was elected in order to achieve lower reporting limits.

- ◇ During the Month 2 and Month 3 events, samples were analyzed for total recoverable arsenic and manganese by EPA 200.7, instead of dissolved arsenic and manganese EPA 200.7. This occurred due to a miscommunication with the lab regarding the required metals analysis.
- ◇ During the Month 3 event, Test America sub-contracted analyses to McCampbell Analytical, Inc, which performed Nitrate as N and Sulfate analyses by Method 300.1, instead of Method 300.0.
- ◇ During the Quarter 2, Quarter 3, and Quarter 4 events, samples were analyzed for dissolved arsenic and manganese by EPA 200.7.

After each monitoring event and upon review of sample results, sampling teams coordinated with laboratories to avoid future deviations. This required scheduling sampling events earlier in the week to avoid shipping delays over weekends, communicating the Work Plan requirements to laboratory staff and managers, and switching shipping carriers. For a complete analysis of the degree to which the work performed for the entire EAB Phase II study complied with specifications from the Work Plan and the QAPP, refer to Appendix G.

4 EAB Performance Results and Discussion

4.1 Data Quality Results

As discussed in Section 3.2.1.3, QA/QC measures were conducted each monitoring event during Phase II to determine the degree to which the work performed complied with specifications from the Work Plan and the QAPP. The Phase II QA/QC evaluation shown in Appendix G examines QA/QC results and procedures in terms of the five data quality objectives established in Section 2.5 of the QAPP: accuracy, precision, completeness, representativeness, and comparability (Locus Technologies, 2020). All Phase II field events, measurements and laboratory results and activities

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underwent a quality control evaluation available in Appendix G. Laboratory QA/QC procedures and/or results that do not meet performance criteria are discussed in Appendix G and have been integrated in the Section 4 discussion, as needed.

4.2 Baseline TCE Conditions

A baseline groundwater monitoring event was conducted at the Site from 14–16 September 2020. The results of this sampling effort were used to characterize initial groundwater conditions and determine appropriate concentrations and volumes of bioremediation injectate to use at each injection boring. At the time of the injection field activities, three exploratory borings were installed to roughly 13 ft-bgs and grab groundwater samples were collected from each. Since TCE is the principal COC at the Site, TCE results from these sampling efforts were used to approximately constrain the lateral extent of VOC contamination within and around the Phase II study area prior to implementing the treatability study. Baseline results were originally reported in the Completion Report. ~~Baseline TCE contours are presented in Figure 4. Baseline concentrations of other constituents are further discussed in Section 4.6.~~

Baseline TCE contours are presented in Figure 4. Baseline concentrations of TCE in the Phase II study area ranged from 17 to 15,000 µg/L at S137A and S140A, respectively. The highest concentrations of TCE are clustered towards the center of the Phase II study area, as delineated by the 10,000 µg/L contour which encompasses S140A and extends slightly eastward towards S158A, S146A, and S138A. The 1,000 µg/L contour is bounded by S159A to the north, S143A to the west, TW-1 to the south, and nearly 15 feet past S146A to the east. Following the general shape of the 1,000 µg/L contour, the 100 µg/L contour is bounded by S049A to the north, S144A to the west, roughly 20 feet past TW-1 to the south, and TW-3 to the west. Baseline concentrations of other constituents are further discussed in Section 4.5.

4.2.1 Well Groupings

Of the fourteen groundwater monitoring locations included in Phase II, ten wells are located inside the reactive zone, which is defined as the area influenced by the ROI of the injections, roughly the Phase II treatability study area seen in Figure 2. These ten wells within the reactive zone have been grouped into three regions to better characterize geospatial trends of the expanded treatability study area. Groundwater wells are grouped in terms of relative baseline TCE concentrations:

1. Low – TCE wells: S137A, S139A and S159A.

Groundwater wells S137A, S139A and S159A are located in the north and northeast region of the reactive zone. Phase II baseline TCE concentrations at these locations range from 17 µg/L to 140 µg/L, refer to Figure 4.

2. The mid-range TCE wells: S141A, S143A and S160A.

Groundwater wells S141A, S143A and S160A are in the northwest region of the reactive zone. Phase II baseline TCE concentrations ranged from 500 µg/L to 1,400 µg/L.

3. The high-TCE wells: S138A, S140A, S146A and S158A.

Groundwater wells S138A, S140A, S146A and S158A exhibit the highest concentrations of TCE and are located in the southern half of the reactive zone. Baseline TCE concentrations ranged from 5,700 µg/L to 15,000 µg/L. The maximum Phase II baseline concentration of TCE was at well S140A at 15,000 µg/L.

Four wells are located outside of the reactive zone of the Phase II treatability study area. Wells S025A and S088A are 364 feet and 120 feet downgradient of the treatability study area, respectively, and are primarily monitored for adverse impacts, refer to Section 4.11. Well S049A is downgradient of the reactive zone and technically beyond the anticipated ROI of injections, but conditions at S049A may be impacted by the reactive zone due to its proximity downgradient

(approximately 40 feet). Well S134A is the only upgradient monitoring well outside of the study area and represents background conditions for this study.

4.2.2 Radius of Influence

The Phase II treatability study injection activities were performed from ~~10/5/19~~ to 20 November 2020, consistent with the test goals in Section 4.14.3 of the ~~Work Plan~~ Workplan. The spacing of injection points was informed by the average ROI documented for the Phase I treatability study. In addition to injection grid expansion, one of the goals of the injection strategy was to confirm the design ROI using groundwater elevation measurements. A summary of results is presented in the sections below.

4.2.3 Radius of Influence Based on Groundwater Elevations

The principle goal for measuring the ROI in this phase of the study was to confirm the observed 20-foot lateral distribution of reagents, thus confirm the adequacy of injection point spacing for future EAB implementation. Injections were delivered over a twelve-point injection grid, spaced 20 feet trilaterally (Figure 5). The ROI for each injection was the resulting distance between the injection point and farthest monitoring well in which mounding of a minimum of 0.5 feet above baseline was measured. In instances when injection activities were commenced in the later hours of the day and completed on the following morning, only groundwater levels from the second day were evaluated for the ROI. This eliminated influences from residual flows of preceding injection activities as groundwater levels attenuated overnight. Groundwater levels monitored for each injection point are shown in Appendix B. ROI evaluation results are summarized below:

ROI Distance	No. Observations
<20 feet	3
20–29 feet	2
30–39 feet	6
>40 feet	1

The influence of delivered injection fluids were monitored using previously installed monitoring wells. Generally, three to four monitoring wells were selected per injection point for mounding observations and to confirm target ROI. When feasible, a minimum of one monitoring well within 20 to 30 feet from injection point was selected. Otherwise, injection monitoring distance was dictated by the location of monitoring well closest to injection point. The selected monitoring wells for each injection location are listed in Table 1 (see daylighting monitoring wells).

A change in elevation of at least 0.5 feet was observed at distances below 20 feet for three injection locations 8, 9, and 10 (Appendix B Figure B-2, B-9, and B-4, respectively). Monitoring of groundwater level for these injection locations was not feasible at distances within 20–30 feet due to existing well configuration. As a result, response to injection delivery was measurable only at nearest monitoring distances between 12 to 15 feet. Injection influences monitored within and outside the 20–30 feet distance range, measurable mounding was observed at 20 feet or greater. A maximum groundwater elevation of 42 feet was observed during injection 11. However, this flow response may have been influenced by preceding injection activities completed on same day (Figure B-13).

To obtain a realistic ROI for this study, the arithmetic average calculation excluded monitoring data for injection location 8, 9, and 10 due to potential data gaps, and for injection 11 due to possible influence from residual flows. The resulting average ROI for this study was approximately 33 feet.

Note that the ROI based on groundwater elevations is not an accurate parameter for measuring the effective lateral distribution of reagents. Mounding effects may have been induced from the combination of lateral displacement of 10% of resident groundwater volume and injected reagent volume. Assuming minimal mixing between reagents and groundwater, the increase in groundwater elevation at distances greater than 20 feet may be influenced by the displaced unamended front or by residual flows from preceding injection activities in the vicinity. Therefore,

a ROI of 20 – 30 feet should be retained for future implementations. Refinement of target ROI may be assisted with employment of tracer studies or similar methods to evaluate site specific fate and transport characteristics and preferential pathways within the treatability zone (Nelson et al, 2005).

4.3 Delivery Techniques

Another test goal was to evaluate injection delivery techniques. This goal was achieved by evaluating direct push tool performance, injection pressure and flowrates at which daylighting and formation fracturing were not observed; and by documenting site-specific fluid volume acceptance capacity.

Prior to the beginning of injection activities, a pre-injection calibration test was conducted within the pilot area. The test consisted of the injection of 10 gallons of potable water at ~~this the INJ-3~~ injection location. The injection test was done to establish flow rates, pressures, and to check for leaks through the delivery system. Injection of remedial reagents was carried out with a Geoprobe 8030 track mounted direct push drill rig with push rod assembly. ~~The goals were to refine injection techniques by evaluating the performance of direct push tools, optimize injection pressures and flowrates, and to document site specific injection-related fluid acceptance capacities.~~

Consistent with Section 4.2 of the Work Plan~~Workplan~~, pressures and flowrates were evaluated as follows: 1) evaluation at one injection point the injection~~evaluation of~~ pressure data was ~~documented~~ at flow rates between 10 to 25 gallons per minute, 2) ~~at another injection point, evaluation of flow rate data was collected at low pressure injections from gravity feed to 25 pounds per square inch (PSI), as based on achieved pressures and flowrates.~~ Fluid acceptance observations were made by evaluating backpressures during the delivery of 'test' injectate

volumes. One test injectate consisted of SRS-SD at 250% above target volume and another of dilution water at 150% above target volume. Completed delivery parameters are seen in Table 1.

4.3.1 Pressure and Flowrate Delivery

The delivery of injection reagents was initiated with a 2.25-inch Pressure Activated Injection Probe (PAIP) (Geoprobe, 2013). This tool is designed with four horizontal injection ports that allows for the radial injection of reagents into the subsurface, in addition to a check valve to prevent back-flow. This injection tool was used at injection locations INJ-3 and INJ-8, which were the first injection points to be installed. The second tooling was a 2.25-inch x 2.5 feet top-down injection probe (TDIP). This tool uses injection ports spread out over the entire injection interval (2.5 feet). This tool was used in all injection points, except at locations INJ-3 and INJ-8. Initial and sustained pressures and average flowrates were monitored at the top of the delivery line at each of the eight intervals. Refer to Table 1 and the Completion Report Appendix E for the Cascade Injection Report.

Sustained pressures and flowrates for INJ-3 were estimated at 70–100 PSI and 3.8 – 20.2 gallons per minute (gpm). At a depth of 31–33.5 bgs, the injection was stopped due to clogging of the tool with clay material. The lowest flowrate (3.8 gpm) was measured at 33.5–36 bgs with a sustained pressure of 90 PSI. The resulting delivery rates were possibly due to the lower transmissive material located at lower depths and not a characteristic of tool performance. At INJ-8, observed pressures and flowrates were 150–170 PSI and 19.5–22.5 gpm, respectively. At this location, initial pressures were generally greater than the achieved sustained rate. At maximum, pressures differed by 50 PSI at the top two intervals. The slight decline in pressure from initial to sustained may indicate the localization of compacted soils that may have resulted from the advancement of the direct push tooling and not as an effect of fracturing (In Situ Remediation Reagents Working Group, 2009).

Injection location 6 (INJ-6) was used a test location to document pressure response to flowrates between approximately 10–25 gpm and flowrate response to low pressures between gravity feed and 25 PSI. The TDIP tool was employed for the injection of reagent at flowrates ranging from 10.1 gpm to 23 gpm. Flowrate adjustments were completed in a ‘step up’ fashion at interval transition. ‘Respond’ pressures increased from 45 PSI to 175 PSI with increasing flowrates. Based on system capacity and site conditions, a flowrate of 10.1 gpm and resulting pressure of 45 PSI were the lowest achievable delivery rates. Therefore, the evaluation of flowrate response to pressures between gravity feed rates and 25 PSI was not feasible. Daylighting was not observed during the injection process at highest flowrate and pressure; thus it is not recommended to continue the low pressure and flow evaluation in this treatability study area since the higher pressures used were not excessive, however for other areas and full-scale application this evaluation may still be necessary. The lower pressure achieved was the minimum observed during the study, therefore, observations on flowrates in response to pressures between gravity feed rates and 25 PSI were not feasible.

4.3.2 Fluid Acceptance Capacity

Fluid acceptance capacity testing was conducted at INJ-5 and INJ-9. The injectate at INJ-5 consisted of SRS-SD emulsion at 250% above target rate, an equivalent injection volume of 593 gallons per interval or total injection volume of 4,744 gallons. The injectate prepared for INJ-9 consisted of an added 150% of dilution water, the equivalent of 862 gallons (50% above target) per interval or total injection volume of 6,989 gallons. Test volumes were delivered at sustained pressures of 170 PSI and at a maximum flow rate of 22.8 and 25 gpm at INJ-5 and INJ-9, respectively. No daylighting or pressure differential was observed.

The collection of pressure and flowrate data provided useful information on effectiveness of direct push injection tooling, sustainable delivery rates, and site-specific fluid acceptance capacity. Overall, the TDIP tooling provided flexibility in the field for delivering the reagent at

various pressures and flowrates. General injection delivery rates were sustained at 170 PSI across the injection column and at flow rates of up to 26 gpm. Similar rates were observed for the delivery of loading volumes of up to 50% above design value. No daylighting or indication of fracturing was observed with the implemented injection techniques.

Observed delivery rates and TDIP tooling are recommended for future implementations, if other delivery parameters (i.e. injection depth, volumes, amendment material, etc.) remain the same. Further refinement of injection techniques may be accomplished by conducting closer inspection of backpressures; specifically, during pre, during, and post injection; to provide higher resolution on potential development of preferential pathways (In Situ Remediation Reagents Working Group, 2009). Additionally, the results of groundwater flow direction and velocity studies may be used to refine the injection layout design.

4.4 Total Organic Carbon (TOC) Retention Time

TOC is an indicator of carbon availability at the site and is used to evaluate substrate distribution. TOC samples were collected consistent with the progress monitoring plan described in the Work Plan (Locus Technologies, 2020). Twelve injections were completed in a period of two weeks from 10 November to 20 November 2020. Sample collection was completed at ten monitoring wells daily (to the extent practicable) during injection activities, monthly for first three months, and quarterly, thereafter. Table 6 includes TOC results from all Phase II sampling events, and a summary of TOC results is available in Table 10 along with other key redox parameters. General TOC retention time at monitoring wells is shown in Figure 6 and concentrations over time are presented in Appendix H (Figure H-1-0 through H-1-13). In addition, Figures 7a through 7g present estimated TOC concentration contours for the reactive zone, which show how TOC concentrations vary over time and space throughout the Phase II study period.

4.4.1 TOC Retention Time

The residence time of TOC within the treatment zone is a direct result of carbon utilization rate and site-specific advective flow. In EAB groundwater remedies, sufficient residence time is necessary to achieve complete degradation of chlorinated compounds. SRS-SD (carbon source) reagent injection volumes for the Phase II EAB pilot study were designed for a single application based on 1) baseline stoichiometric demand using the ER-200627 Loading Substrate Tool (Parsons, 2010) and 2) target dosing of 500 mg/L of TOC at the injection point. For this study, TOC was used as a surrogate for evaluating reagent distribution and longevity across the treatment zone over a period of 12 months (design cycle). Generally, TOC values above 20 mg/L are ideal to sustain biological degradation of VOCs (EPA, Bioremediation Anaerobic Bioremediation (Direct), 2021). The longevity of the reagent will elucidate the effectiveness of design dosage and reagent delivery frequency.

~~TOC samples were collected consistent with the progress monitoring plan described in the Workplan (Locus Technologies, 2020). Twelve injections were completed in a period of two weeks—six completed on 13 November and remaining on 20 November 2020. Sample collection was completed at ten monitoring wells daily (to the extent practicable) during injection activities, monthly for first three months, and quarterly, thereafter. General TOC retention time at monitoring wells is shown in Figure 5 and concentrations over time are presented in Appendix H (Figures H-1-0 through H-1-13). Table 6 reports TOC results from all Phase II sampling events, and a summary of TOC results is available in Table 10 along with other key redox parameters.~~

4.3.2.14.4.1.1 Non-Reactive Zone TOC

Four wells were evaluated collectively as 'background' or non-reactive zone wells. Sample locations S025A and S088A are a set of distal downgradient wells designated for monitoring water quality impacts. Well S049A is located adjacent and downgradient of the treatment area, and S134A is a background reference well located upgradient (see Figure 2). The initial post

injection sampling event in 15–18 December 2020 (Month 1) was completed 25 days following injection activities. Minimal change to TOC concentration was observed in the four background wells throughout the study period. The arithmetic average of baseline and post injection TOC was 1.90 mg/L and 2.15 mg/L (13% difference), respectively. No appreciable changes to TOC concentrations were observed following the first post-injection sampling event. Average TOC in the fourth quarter was estimated at 1.65 mg/L.

4.3.2.24.4.1.2 Reactive Zone TOC

TOC retention time was evaluated using data from monitoring wells within the Phase II reactive zone (treatability area), as shown in Figure 65. Following this approach, data from background wells were omitted. A summary of TOC across the treatment zone is presented below:

Sampling Event	Avg. TOC (mg/L)	% Diff in avg TOC	Min (mg/L)	Max (mg/L)	No. locations with TOC ≥20 mg/L
<u>14-16 September 2020</u> (Baseline)	1.9	--	1.0	2.4	--
<u>10-13 November 2020</u> (Post injection – end week 1)	38	1900%	1.5	250	7
<u>16-20 November 2020</u> (Post injection – end week 2)	120	210%	2.9	580	8
<u>15-18 December 2020</u> (Month 1)	110	-8.0%	6.7	410	8
<u>18-20 January 2021</u> (Month 2)	110	-5.0%	3.5	510	7
<u>15-17 February 2021</u> (Month 3/Quarter 1)	79	-24%	1.2	460	6
<u>17-19 May 2021</u> (Quarter 2)	28	-65%	2.3	150	3
<u>17-19 August 2021</u> (Quarter 3)	34	20%	1.2	210	3

8-10 November 20212021Q4 (Quarter 4)	19	-43%	0.86	130	2
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The highest TOC averaged 120 mg/L at the conclusion of injection activities (week 2). TOC tapered following this period, with greatest decrease (65%) occurring in transition to second quarter monitoring event 17–18 May 2021 (between 90 and 180 days). Progressive decline followed until the fourth quarter event in 8–10 November 2021 during which TOC levels ranged from 0.86 mg/L to 130 mg/L and averaged of 19 mg/L.

As seen in the above table, TOC levels above 20 mg/L were sustained at six out of ten monitoring locations through the Month 3 event on 15–17 February 2021 (for up to 90 days after injections/Q1). (month 3), following injection activities. The number of locations with target levels was reduced to three by 17–18 May 2021 (day 180/ (Q2), and further reduced to two by end of pilot study 8–10 November 2021 (Q4). Target TOC levels were not achieved at well location S160A and poorly retained at S141A. These wells are located upgradient of the existing groundwater extraction trench. Although the extraction trench was not operated throughout the pilot, possible natural velocity gradients through the porous material of the trench may be attributing to poor retention of amendment at these locations. Additionally, rapidly decreasing TOC levels were observed at monitoring wells located immediately downgradient from injection points (S137A, S138A, and S159A). The evaluation of other lines of evidence may provide insightful data on whether the rapid decline may be attributed to microbial activity and or high advective flow. The approximate retention time over the course of the study period at each sample location is depicted in Figure 665.

The injection of SRS–SD resulted in a TOC increase from 1.8 mg/L to an average of 120 mg/L by end of second week of injectionsinjections 16–20 November 2020. Average concentration gradually decreased following this period and with greater reduction by second quarter. Based

solely on TOC data, the results suggest an increase in injection frequency or dosing concentration may be required for a 12-month design cycle. However, the depletion may be attributed to the effects of potential groundwater velocity gradients resulting from existing preferential pathways, in addition to its utilization for biotic degradation. Further refinement of amendment dosing and frequency may be assisted with the evaluation of biodegradation rates and from site-specific studies on groundwater velocity gradients across the treatment zone.

4.4.2 TOC Concentration Trends

Prior to Phase II injections, TOC concentrations were relatively constant across ~~monitoring the~~ ~~sampling locations~~ ~~locations~~ wells, both inside and outside the reactive zone, and ranged from 1 mg/L to 2.4 mg/L during baseline monitoring in 14–16 September 2020. However, injections created high variability in TOC concentrations across the study area. ~~Figures 7a through 7g~~ present estimated TOC concentration contours, which show changes in TOC concentrations over time and across the reactive zone. The first TOC concentration contour figure, ~~Figures 7a~~, shows TOC results from samples collected approximately two weeks after injections on 20 November 2022, and the final TOC contour figure, ~~Figure 7g~~, shows conditions at the time of the fourth quarter sampling event 8–11 November 2021. In general the highest TOC concentrations were first observed at the northeast side of the reactive zone, and the lowest concentrations ~~concentration~~ were at the northwest side of the reactive zone (see ~~Figure 7a~~). By the end of the performance period, the higher TOC concentrations appeared on the south side of the reactive zone (see ~~Figure 7g~~). ~~Table 6 contains all TOC results from Phase II.~~

~~All In addition, TOC concentrations measured throughout the Phase II study period are~~ ~~Phase II~~ TOC results are also ~~presented~~ presented in time series plots in Appendix H (Figures H-1-0 through H-1-13). The Y-axes of these plots show TOC concentrations that range from either 0–250 mg/L or 0–600 mg/L for reactive zone wells (Figures H-1-4 through H-1-13), depending on the maximum TOC observed. The constant Y-axes aid in the visualization of TOC distribution

and depletion over time. These plots also identify injection start dates and the 20 mg/L TOC concentration threshold for sustaining biological degradation of VOCs (EPA, Bioremediation Anaerobic Bioremediation (Direct), 2021). Phase II TOC concentrations measured at the non-reactive zone wells are also plotted in plots shown in Appendix H (Figures H-1-0 through H-1-3).

As shown in Appendix H time series plots, the injections in November 2020 caused TOC to increase to above 20 mg/L at every well inside the reactive zone, while the non-reactive zone wells did not surpass TOC concentrations over 3 mg/L through Phase II. The maximum TOC concentration of 580 mg/L was detected at well S159A on the final day of injections, 20 November 2020. Of the reactive zone wells, S141A and S160A recorded the lowest TOC concentrations and most rapid depletions, refer to Figures H-1-8 and H-1-13 in Appendix H, respectively. The depletion at S141A and S160A is also visible in Figure 7a, which shows how the TOC concentrations at these wells was already below the 20 mg/L threshold by the final day of injections, 20 November 2020.

In general, the trend in TOC for Phase II is a peak in the reactive zone, is TOC peaked during injections in November 2020, then followed by a steady decline and approached that approaches baseline conditions by the fourth quarter. This is the case for wells S137A, S138A, S139A, S140A, S141A, S146A and S160A, as shown in Appendix H plots. There were a few exceptions. TOC concentrations at well S159A remained high through February 2021 (90 days after injections), shown in Figure 7d, before steady depletion. At well S143A, shown in Figure H-1-9, TOC was ideal until February 2021 (90 days after injections), then decreased to below 20 mg/L refer to Appendix H Figure H-1-9. Well S158A stabilized through the first quarter monitoring event in February 2021 at around 120 mg/L of TOC, increased during the second and third quarters, and finally decreased back down to 130

mg/L in the fourth quarter monitoring event in November 2021. By the fourth quarter monitoring event, only S158A was above the 20 mg/L TOC threshold, refer to Figure 7g, H-1-11. Wells S138A and S159A were just below the TOC threshold at 18 mg/L and 19 mg/L, respectively, in the fourth quarter. Table 6 contains all TOC results from Phase II.

In addition, TOC concentrations measured throughout the Phase II study period are presented in time series plots in Appendix H (Figures H-1-0 through H-1-13). The Y axes of these plots show TOC concentrations that range from either 0-250 mg/L or 0-600 mg/L for reactive zone wells (Figures H-1-4 through H-1-13), depending on the maximum TOC observed. The constant Y axes aid in the visualization of TOC distribution and depletion over time. These plots also identify injection start dates and the 20 mg/L TOC concentration threshold for sustaining biological degradation of VOCs (EPA, Bioremediation Anaerobic Bioremediation (Direct), 2021). Phase II TOC concentrations measured at the non-reactive zone wells are plotted in plots shown in Appendix H Figures H-1-0 through H-1-3.

Declining TOC levels in conjunction with elevated VOCs and the presence of alternate electron acceptors may indicate that additional substrate is required to sustain the anaerobic environment (EPA, Bioremediation Anaerobic Bioremediation (Direct), 2021). Within the Phase II study area, elevated concentrations of the alternate electron acceptor sulfate persisted, especially at wells S140A, S141A and S160A, refer to Table 10. As mentioned, these wells also had low TOC retention times. While preferential pathways and groundwater gradients may play a role in TOC depletion as discussed in Section 5.3, ~~Error! Reference source not found.~~ 4.5.1, elevated sulfate in the study area (concentrations above 20 mg/L) may also contribute to depletions in TOC. Sulfate concentrations are discussed further in Section 4.6.5.

4.4.4.5 Volatile Organic Compounds (VOCs)

Section 1.1 discusses the ten COCs identified at the Signetics Site. Historical monitoring has shown TCE to be the predominant COC in the treatability study area, so TCE serves as the

indicator chemical for the study. The aim of Phase II is to assess EAB as a viable technology for reducing COCs to acceptable concentrations. TCE concentrations are evaluated against the cleanup standard (action level) of 5 µg/L TCE, originally established in the ROD. Cleanup standards were determined for all COCs in the ROD, however the use of the standards in this EAB evaluation was limited to TCE and two daughter products, cis-DCE and vinyl chloride, with action levels of 6 µg/L and 0.5 µg/L, respectively. Concentrations of TCE and its daughter products were monitored throughout Phase II, and results are shown in the time series plots in Appendix H (Figures H-2-0 through H-2-27 show molar concentrations of VOCs; Figures H-3-0 through H-3-27 show VOC concentrations in units of micrograms per liter).⁷

Besides TCE and its daughter products, the other prevalent COC at the study area is Freon 113. High concentrations of Freon 113 have been shown to cause stalling in the reductive dechlorination process. Freon 113 concentrations are discussed in Section 4.9. Refer to Appendix H for time series plots of Freon 113 relative to TCE and cis-DCE.

The other Signetics Site COCs are not included in this discussion because concentrations are relatively low compared to chlorinated ethene concentrations in the reactive zone; however, sample results are available in laboratory reports attached in Appendix F. For instance, chloroform was below detection at all locations during Phase II; chlorinated ethanes (1,1,1-TCA and 1,1-DCA) are found at orders of magnitude less than TCE and cis-DCE; and 1,1-DCE is a less common daughter product of TCE.

Phase II results are available in accompanying tables and appendices. Groundwater level measurements and field parameters are shown in Table 4. Analytical data for all wells are shown on Table 6. Temporal concentration plots are available in Appendix H. Associated analytical laboratory reports are included in Appendix D.

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4.4.14.5.1 TCE Mass Removal

The change in mass of TCE as a result of Phase II injections can be calculated by comparing the baseline TCE mass to fourth quarter TCE mass. This method, shown in Table 8, estimates how many pounds of TCE were removed through a comparison of baseline and fourth quarter TCE analytical contours shown in Figure 4 and Figure 8, respectively. First, the area between each TCE contour (<100 µg/L, <1,000 µg/L etc.) is multiplied by an assumed saturated aquifer thickness of 20 feet and porosity of 0.36 (Locus Technologies, 2021), which converts each contour area into an "A" aquifer groundwater volume. Next, the geometric mean TCE concentration is calculated for wells located inside each contour area. The TCE mass is derived by multiplying each groundwater volume by each respective geometric mean TCE concentration. These calculations are performed for both baseline and fourth quarter TCE analytical contours, and total mass removed is calculated by subtracting the fourth quarter TCE mass from the baseline TCE mass.

Table 8 shows calculated values for baseline and fourth quarter TCE plume areas, geometric mean TCE concentrations, and the estimated TCE mass. The mass of TCE removed from the treatability study area during Phase II can be estimated from the TCE contours in Figure 4 (baseline) and Figure 6 (fourth quarter). To perform this calculation, the geometric mean TCE concentration of wells between each contour line is calculated. Areas between each contour were then geospatially delineated and estimated for the study time frame. Based on the delineated TCE plume areas in Figure 4 and Figure 6, as well as geometric mean TCE concentrations of the plume, a site-specific average total porosity of 0.36 (Locus Technologies, 2021) and a 20-foot saturated aquifer thickness, the TCE mass removal can then be estimated. Table 8 Example calculations, conversion factors and assumptions are provided on page 2 of Table 8. shows the results of this analysis. This mass removal e-analysis indicates estimates that the TCE mass of TCE was approximately 19.0 pounds at the time of baseline monitoring in September 2020 and was reduced to 1.1 pounds at the time of fourth quarter monitoring in November 2021, which is a

reduction of approximately 17.9 pounds (94% reduction) as a result of the Phase II pilot study. Figure 9 shows both baseline and fourth quarter TCE concentrations. The decrease in the area with higher concentrations indicate the TCE plume is shrinking in the treatability area.

4.5.2 Concentration Trends

The following sections discuss VOC concentration trends at the low, mid-range and high-TCE well groups within the reactive zone (see Section 4.2.1 Well Groupings). Plots showing these trends are included in Appendix H. Plots were made for each well in the standard reporting unit, $\mu\text{g/L}$ as seen in Figure H-3-0 through H-3-13 (Appendix H). Plots were also converted to moles/liter to facilitate one-to-one comparison of the parent and dechlorination products as seen in Figures H-2-0 to H-2-13.

4.4.1, 4.5.2.1 Low-TCE wells

Concentrations of TCE ranged from 17 $\mu\text{g/L}$ to 140 $\mu\text{g/L}$ at the low-TCE wells during the baseline monitoring event in September 2020 (refer to Figure 4). By the fourth quarter monitoring event in November 2021, TCE concentrations were reduced by 93%, 29%, and 99.8% at S137A, S139A and S159A, respectively, as seen in Table 9 (page 1). This section describes the degradative pathways and VOC concentration trends observed during Phase II. ~~Plots showing these trends are included in Appendix H. Plots were made for each well in the standard reporting unit, $\mu\text{g/L}$ as seen in Figure H-3-0 through H-3-13 (Appendix H). Plots were also converted to moles/liter to facilitate one-to-one comparison of the parent and dechlorination products as seen in Figures H-2-0 to H-2-13.~~

Molar plots indicate that TCE decreased as a result of the injection at well S137A (INJ-2) and the dechlorination products were generated. Although not clear from the data, it is suspected that cis-DCE increased within the first 30 days, then decreased as expected in the VOC degradation

process. Vinyl chloride peaked initially at 30 days, then decreased. Ethene increased until 60 days then stabilized. Both cis-DCE and vinyl chloride began rebounding after the second quarter or 180 days after injections. As mentioned earlier, the TOC retention time at this well was 90 days, indicating the ideal 20 mg/L TOC needed to sustain anaerobic treatment was not available. Additional substrate is likely needed in the area of this well to continue degradation.

The dechlorination product generation was less clear in well S139A. TCE decreased 30 days after injections at INJ-7 but then began rebounding. Cis-DCE and vinyl chloride exhibited a similar trend and rebounded after 30 days. Ethene was generated with a peak at 30 days. The TOC retention time at this well was 90 days, thus substrate was still available during the rebounding. Other factors besides substrate amount may be contributing to rebound at this well. Compared to the other low-TCE wells, S139A is located closer to the baseline 10,000 µg/L TCE area of the plume, shown in Figure 45. Rebounding that occurred at in S139A may be the result of influenced by groundwater transport of VOCs from higher concentrated areas of the plume. Sources of rebounding are discussed further in Section 4.5.1.

S159A exhibited an ideal parent and dechlorination daughter product trend. While TCE decreased in response to the injection at INJ-4, cis-DCE increased and reached its peak after 30 days at which point began to decrease. Vinyl chloride began to increase after injections and peaked around 60 days after injections before it decreased. Ethene was generated, peaked 90 days after injections, then decreased. Rebounding did not occur in this well. The TOC retention time was four quarters. COC concentrations decreases in this well are thus attributed to reductive dechlorination.

After injections, TCE concentrations at wells S137A and S139A decreased to below the action level of 5 µg/L after 30 days as seen in Table 9. Well S159A reached the TCE action level shortly thereafter (at 60 days <10 µg/L TCE; 90 days 1.6 µg/L TCE). For the remainder of Phase II, TCE was below the action level at wells S137A and S159A.

Concentrations of cis-DCE also dropped below the action level of 6 µg/L after 90 days at S137A and after two quarters (180 days) at S159A. Cis-DCE, however, began to rebound above the action level at S137A in the third quarter. Cis-DCE also rebounded in S139A after 90 days and resulted in a higher concentration than Phase II baseline and a return to the original Phase I concentration. Vinyl chloride reached a maximum concentration 30–60 days after injections at the low-TCE wells. Vinyl chloride remained elevated at S137A and S139A, but decreased at S159A, meeting the action level in the fourth quarter. Well S159A was the only groundwater well in the reactive zone to achieve complete dechlorination during Phase II because all COC action levels met within the Phase II timeframe. The fourth quarter vinyl chloride concentrations in wells S137A and S139A were higher than the Phase I and Phase II baselines, indicating reductive dechlorination of TCE and cis-DCE is occurring to generate this daughter product, however additional substrate is needed to complete the degradation pathway.

~~4.4.1.24.5.2.2~~ Mid-range TCE wells

Baseline monitoring indicated the predominant COCs at the mid-range wells were TCE and cis-DCE. TCE concentrations in September 2020 ranged from 500 µg/L to 1,400 µg/L ~~at the mid-range wells, shown in Figure 4. At the end of~~ By the fourth quarter of Phase II, TCE concentrations were reduced by 71%, 99.8% and 68% at S141A, S143A and S160A, respectively as seen in Table 9 ~~(page 2).~~ This section describes the degradative pathways and VOC concentration trends observed during Phase II. Final TCE contours for the treatability study area are shown in Figure ~~876~~, and plots showing TCE trends are included in Appendix H.

The molar and concentration plots for S141A, located at the north edge of injections, indicate TCE decreased as a result of the nearby injection (INJ-7) ~~yet it rebounded after 90 days. Cis-DCE was generated and peaked after 30 days after which it decreased and returned to the original cis-DCE concentration. Vinyl chloride peaked after 60 days then slowly decreased, yet decreased yet remains above the baseline concentration. Ethene was generated and peaked after 60 days at~~

which time it stabilized. The TOC retention time was days at this well, indicating that the ideal 20 mg/L TOC needed to sustain anaerobic treatment was not available. Additional substrate is likely needed in the area of this well to continue degradation.

Well S160A, located about 25 feet northeast of S141A, exhibited a TCE decrease then rebounded after 30 days. Cis-DCE did not peak as expected during the reductive dichlorination process, however it decreased throughout the performance time period. Vinyl chloride also did not peak as expected, yet expected yet decreased and stabilized. Ethene was not generated in this well when compared to baseline, however the baseline concentration is unusually high when compared to other wells. Due to the lack of expected trends, sustained reductive dechlorination did not occur in this well. The TOC retention time was days, indicating that the nearby injection (INJ-7) had little impact minor impact at S160A.

In well S143A, located on far west side of the Phase II treatability study area, TCE decreased as a result of injections at INJ-10 until 90 days after the injection, at which point TCE began a slight rebound. Cis-DCE increased and peaked 30 days after injections, then decreased until it rebounded after the third quarter (270 days post injection). Vinyl chloride also peaked 30 days after injections and rebounded after the third quarter. Ethene increased until 60 days after injections at which point it stabilized. The TOC retention time was nearly two quarters in this well, indicating that the ideal 20 mg/L TOC needed to sustain anaerobic treatment was not available. Additional substrate is likely needed in the area of this well to continue degradation.

Despite the lack of the ideal amount of TOC to sustain treatment in the mid-range TCE wells, there was an immediate response to injections. One month after injections, TCE concentrations decreased by 81.4%, 97.0%, and 98.0% at S141A, S143A and S160A, respectively (see Table 9 page 2). At well S141A, the minimum TCE concentration observed was 220 µg/L at the 90-day post-injection event. Cis-DCE at S141A initially increased after injections and decreased gradually during every monitoring event thereafter. After 60 days, vinyl chloride reached a

maximum of 260 µg/L at well S141A and remained above baseline concentration through the fourth quarter. Action levels were not met for any COCs at S141A, however final concentrations in this well were lower than the Phase I baseline values for all COCs except TCE and Freon 113.

Well S143A met the action level goals for TCE and cis-DCE after 60 days but rebounded slightly in the fourth quarter (cis-DCE 24 µg/L; TCE 9.7 µg/L). Vinyl chloride peaked after 30 days and approached the action level between days 60 and 90, before rebounding in the fourth quarter. Ethene concentrations at S143A increased from below detection at baseline to 950 µg/L after 60 days. All final COC concentrations at this well were lower than Phase I baseline concentrations, except for vinyl chloride. Fourth quarter Phase II results are approaching action levels, except for vinyl chloride.

Due to elevated reporting limits (where sample dilution was needed to quantify cis-DCE), it is unclear if TCE action levels were ever reached at well S160A, although TCE concentrations approached action levels during two monitoring events (TCE <10 µg/L after 30 days; TCE <25 µg/L after 60 days). Cis-DCE concentrations were reduced by nearly 50% in Phase II but remained above action levels. Cis-DCE and TCE rebounded slightly in the fourth quarter. Well S160A had the highest baseline ethene concentration of all wells and vinyl chloride concentrations were much higher than other mid-range wells. However, concentrations of ethene and vinyl chloride decreased 30 days after injections and remained low through the fourth quarter. As discussed earlier, based on daughter product trends, these decreases are likely not due to reductive dechlorination.

~~4.4.1.34.5.2.3~~ High-TCE wells

During baseline monitoring, groundwater wells S138A, S140A, S146A and S158A had the highest concentrations of TCE, cis-DCE and Freon 113 of all the wells in the study area. These wells are located in the middle of the Phase II treatment area. Wells S138A, S140A, and S146A are also within the Phase I injection ROI. At the time of baseline sampling, cCis-DCE is was the

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predominant COC at the high-TCE wells, except at well S146A where the TCE concentration was slightly higher (5,700 µg/L TCE; 4,200 µg/L cis-DCE), which could be attributed to Phase I treatment efforts

Fourth quarter results show TCE was reduced from baseline concentrations by 99.9%, 98.7%, 28.1%, and 99.9% at S138A, S140A, S146A and S158A, respectively as seen in Table 9 (page 3). Well S146A (28.1% reduction from baseline to Q4) achieved 96.5% reduction 60 days after injections but rebounded to baseline levels by the fourth quarter sampling event. An explanation of VOC rebounds is described in Section 4.5.1. This section describes the degradative pathways and VOC concentration trends observed during Phase II. Plots showing these trends are included in Appendix H.

After TCE was reduced in well S138A following injections at INJ-5, cis-DCE decreased approximately 30 days post-injection as seen in the Appendix H ~~molar~~ plot (Figure H-3-5). It is suspected that the cis-DCE peak occurred within the first thirty days. Cis-DCE continued to decrease through 90 days (decrease of 92% from baseline) at which point it began to stall above action levels. Vinyl chloride began to increase after 30 days and peaked at 90 days post-injection (increase of 2,000% from baseline). After decreasing for two quarters, vinyl chloride rebounded slightly in the fourth quarter. Ethene exhibited an increasing trend through the post-injection monitoring process. By the fourth quarter, all COCs were above action levels at S138A, although the reporting limit for TCE was elevated (TCE result of non-detect <10 µg/L). While rebound occurred, these trends indicate reductive dechlorination is occurring at this well. The TOC retention time at this well was four quarters, indicating substrate is still available to sustain anaerobic treatment. Thus rebound is likely due to a factor other than lack of substrate. Further monitoring is also recommended to see if the remaining substrate may continue to aid in degradation.

TCE in well S140A decreased substantially in the first 30 days, rebounded then decreased again after 90 days post-injection. Cis-DCE was high in this well at the start of injections and slightly increased 60 days post-injection. Cis-DCE returned to near baseline by the end of the performance timeframe. Vinyl chloride increased after 30 days, decreased, then rebounded after at 27090 days. Ethene increased from baseline, slightly decreased, then resumed increasing. The nearby injection was INJ-8. TOC retention time at this wall was 60 days, indicating the ideal 20 mg/L TOC needed to sustain anaerobic treatment was not available. Additional substrate is likely needed in the area of this well to continue degradation.

TCE initially decreased in well S146A, then rebounded after 960 days post-injection (see Appendix H molar plot in Figure H-2-10).- Cis-DCE increased and peaked after 60 days then decreased until the third quarter, after which it rebounded. Vinyl chloride increased and peaked during the second quarter (although the analysis was out of hold), then decreased before slightly rebounding after third quarter. Ethene did not appear to increase during the performance timeframe. The rebounding and lack of ethene generation indicate reductive dechlorination was limited. In addition, the TOC retention time at this well was two quarters, indicating the ideal 20 mg/L TOC needed to sustain anaerobic treatment was not available. Furthermore, the injection delivery tool used at the nearest upgradient injection point (INJ-3) was the PAIP instead of the TDIP used at other injection locations. Using this tool, sustained pressures and flowrates were limited at 70-100 PSI and 3.8 – 20.2 gpm with periodic tool clogging. Additional substrate will be needed in the area of this well to continue degradation, and it is recommended that the TDIP be used instead of the PAIP to ensure adequate injectate distribution.

Well S158A, located on the southern end of the Phase II treatability area and within the ROI of INJ-9, exhibited reductive dechlorination trends for much of the performance monitoring period (see Appendix H molar concentration plot in Figure H-2-11).-TCE decreased until the third quarter after which it rebounded. Cis-DCE increased by 286% 30 days after injections, peaked 60

days after injections, then decreased to below baseline, however rebounded after the third quarter. Vinyl chloride increased until the second quarter, decreased, then rebounded after the third quarter as well. Ethene was generated in this well as a result of the reductive dechlorination process and stabilized after the second quarter. By the fourth quarter, all COCs were above action levels at S158A, although the reporting limit for TCE was elevated (TCE result of non-detect <10 µg/L). The TOC retention time in this well is four quarters and contained 210 mg/L TOC, substantially above the recommended amount. Because the rebound occurred in fourth quarter sampling event, further monitoring is recommended in this well to ensure these concentrations are not anomalous.

While rebounding occurred frequently in the high-TCE wells, TCE was readily reduced following injections. After 30 days, TCE decreased by 96%, 97%, 94% and 68% compared to baseline conditions at S138A, S140A, S146A and S158A, respectively. Cis-DCE remained high or increased after 30 days with concentrations ranging from 8,500 µg/L to 44,000 µg/L. High cis-DCE concentrations resulted in elevated reporting levels for VOCs other than cis-DCE during Phase II, especially for these high-TCE wells. This is due to sample matrix interference where analytes present at very high concentrations interfere with the laboratory's ability to accurately detect analytes present at very low concentrations (refer to Appendix G). Although the TCE action level may have been met during the first and fourth quarters (the reporting levels were elevated at 50 µg/L and 10 µg/L, respectively), the only result confirmed to meet the 5 µg/L action level was S158A in the third quarter when cis-DCE concentrations significantly decreased and TCE was detected at 2 µg/L.

As previously mentioned, cis-DCE stalled at S140A and S146A during Phase II, with final cis-DCE concentrations near or above baseline concentrations. In the Phase I evaluation report, stalling of cis-DCE degradation at S140A was linked to high Freon 113 concentrations (Locus Technologies, 2018). Freon 113 inhibits reductive dechlorination by DHC (specifically *Dehalococcoides mccartyi*)

in a concentration-dependent manner, causing cis-DCE stalls (Im J, 2019). The relationship between concentrations of Freon 113 and stalling of cis-DCE degradation is discussed in the Freon Concentrations Section 4.9.

4.4.14.5.1 VOC Stalls and Rebounds

One of Phase II Work Plan Test Goals listed in Section 2 is to mitigate VOC rebounds by increasing the carbon availability across the study area. The VOC concentration trends reviewed in Section 4.5.2 identified instances of potential stalling and/or rebounding at monitoring locations in the treatability study area and attributed much of the rebounding to lack of substrate retention time. This section discusses additional potential reasons for VOC stalls and rebounds at EAB sites.

Stalling refers to concentrations of VOC that remain relatively constant over time. The reductive dechlorination process may stall, even under favorable reducing conditions, if concentrations of competing compounds are elevated. For example, during Phase I, high sulfate and Freon 113 were observed to cause potential stalling inside the reactive zone (Locus Technologies, 2018).

Studies have shown that stalling at cis-DCE and vinyl chloride can occur if elevated sulfate concentrations coexist with low TOC concentrations (EPA, Bioremediation Anaerobic Bioremediation (Direct), 2021). Stalling at cis-DCE may also result if Freon 113 concentrations are elevated. Studies show Freon 113 inhibits reductive dechlorination by DHC (specifically DHC *mccartyi*) in a concentration-dependent manner, causing cis-DCE stalls (Im J, 2019). Finally, stalling may also arise if reducing conditions are insufficient. Under mildly anaerobic conditions, vinyl chloride may accumulate at a faster rate than vinyl chloride is degraded, causing concentrations of VOCs to stabilize (Parsons, 2004).

Rebound is a post-treatment phenomenon that causes aqueous-phase VOC concentrations to increase following sharp declines in VOC concentrations. There are a few common causes of rebound. Rebounding caused by groundwater transport (advection) may cause a rebounding effect at downgradient wells, especially if the upgradient wells contain very high VOC

concentrations comparatively (Air Force, 2007). Rebounding may also arise from diffusion of VOCs from high concentration areas to lower concentration areas. Also, low concentrations. Rebounding—rebounding of VOCs after initial improvement may be caused by matrix back-diffusion, which occurs when VOCs that adsorbed onto aquifer sediments or other constituents are later released back into the aqueous phase from diffusive forces (ITRC, 2020). At enhanced in-situ sites using applying a SRS-SDa carbon substrate, rebounding can may appear due to a phenomenon called sequestration, in which VOCs in the groundwater partition into the substrate after injections, substantially reducing VOC concentrations in the aqueous state. As unpartitioned VOCs are degraded in the aqueous state, additional chlorinated solvent mass will be released from the substrate due to equilibrium partitioning, causing a rebound in VOC concentrations (Air Force, 2007).

4.54.6 Redox conditions

Reduced environments are characterized by diminished levels of dissolved oxygen (DO) and by strongly negative oxidation–reduction potential (ORP) values (EPA, 1998). In a groundwater environment with sufficient carbon substrate, native electron acceptors are reduced in the following sequence (from most readily reduced to only reduced in strongly reducing environments): nitrate, manganese, ferric iron, sulfate, then carbon dioxide (methanogenesis). Similarly, reductive dechlorination of ethenes and ethanes is promoted under reduced conditions. The more highly chlorinated (more oxidized) VOCs, such as PCE and TCE, tend to reduce more readily under anaerobic conditions, and the less-oxidized VOCs, such as cis-DCE and vinyl chloride VC, are already somewhat reduced and require more reduced conditions (EPA, Bioremediation Anaerobic Bioremediation (Direct), 2021). Insufficient redox conditions may lead to accumulations of these less-oxidized VOC, refer Section 4.5.1, which discusses cis-DCE and vinyl chloride stalls.

Monitoring electron acceptors and VOC species over time provides multiple lines of evidence necessary to evaluate the remedial effectiveness of EAB applications. Table 10 presents a summary of key redox species for ease of comparison over time at each monitoring well.

Table 4 and Table 6 include all post-injection groundwater quality monitoring data.

4.5.14.6.1 Oxidation Reduction Potential

The ORP of groundwater provides data on whether or not anaerobic conditions are present. This measurement alone is insufficient and must be used in conjunction with other geochemical parameters to express the extent of the reducing conditions in groundwater. In general, positive ORP values in conjunction with elevated DO and absence of substrate can indicate that additional substrate is required to promote reductive dechlorination by biodegradation. However, if ORP measurements are negative, the likelihood of reductive dechlorination can be estimated by the magnitude of the negative ORP measurement. For example, ORP less than –50 mV indicates reductive dechlorination is possible, ORP values less than –100 mV means dechlorination is likely, and ORP under –150 mV is ideal. Plots showing DO and ORP are available in Appendix H (Figures H-4-0 through H-4-13).

During the baseline monitoring event, ORP values ranged from +120.9 mV to –144.6 mV in the reactive zone. The only positive ORP measurements were detected in the mid-range TCE wells in the northwest region of the reactive zone (S141, S143A, and S160A). All other wells in the reactive zone had negative ORP values during baseline monitoring, with the high-TCE wells registering the most strongly negative ORPs. The ORP measurements decreased during the injection period from 10111–20 November 2020 as seen in Table 2. After 30 days, ORP values ranged from –116.0 mV to –310.2 mV in the reactive zone, indicating favorable reducing conditions for dechlorination. The most strongly negative ORP values were detected in the center of the treatability study area at the high-TCE wells.

All monitoring wells in the reactive zone remained below baseline ORP values through the final post-injection monitoring event in November 2021. However, two mid-range wells, S141A and S160A, had marginal ORP values in the fourth quarter (-70.7 mV and -55.7 mV, respectively). These mid-range wells also had the highest ORP values (least reducing) during baseline monitoring. The ORP values remained in the favorable range for dechlorination through the fourth quarter at the high-TCE and low-TCE wells (<-100 mV ORP).

4.5.24.6.2 Dissolved Oxygen

The extent of reducing conditions in groundwater can be informed by DO measurements. DO must be depleted to less than 0.5 mg/L in the groundwater in order to establish a reductive dechlorination pathway (EPA, Bioremediation Anaerobic Bioremediation (Direct), 2021). Plots showing DO and ORP are available in Appendix H (Figures H-4-0 through H-4-13). Baseline monitoring from September 2020 confirmed that the subsurface of the reactive zone was at an anaerobic state (< 0.5 mg/L) prior to Phase II injections, except for one monitoring location that was slightly above the DO threshold (S143A at 0.7 mg/L). Up-gradient and down-gradient wells were also below the DO threshold, which is not expected outside the reactive zone, thus baseline DO measurements may not be representative.

During injections on 10–20 November 2020, DO temporarily increased within the reactive zone and immediately downgradient at S049A. DO concentrations returned to below 0.5 mg/L at all monitoring locations in the reactive zone 30 days after injections, except for at two monitoring wells that were still slightly elevated (S141A 0.53 mg/L; S137A 0.57 mg/L). DO concentrations were below 0.5 mg/L at all locations in the reactive zone during 60 days after injections, ranging from 0.22 mg/L to 0.45 mg/L, refer to the DO concentrations in the summary of redox conditions in Table 10.

Field technicians encountered an instrumentation error during the Month 3 monitoring event on 15–17 February 2021. DO was elevated at all monitoring locations in the reactive zone and ranged

from 1.19 mg/L to 1.39 mg/L. Field technicians performed a re-sampling event the following month on 15–16 March 2021 using two YSI Pro–DSS meters arranged in parallel to collect replicate field measurements at all monitoring locations in the reactive zone. The resampling event confirmed DO in the reactive zone was not elevated (DO ranged from 0.37 mg/L to 0.54 mg/L). The DO probe in the YSI Pro–DSS is highly sensitive to salinity and temperature, and long-term exposure chemicals such as chlorinated solvents can alter the sensor’s performance (YSI Incorporated, 2009). After the re-sampling event, calibration procedures changed (see Field QAQC section of Appendix G for details).

Despite more stringent calibration regimes, field technicians encountered another instrumentation error during the Quarter 2 monitoring event in May 2021. DO concentrations were elevated at all monitoring locations in the reactive zone (1.92 mg/L to 2.70 mg/L). Field technicians continued to collect DO measurements using the YSI Pro–DSS meter during the Quarter 3 and Quarter 4 monitoring events; however, the optical probe materials could potentially be damaged from the presence of solvents in the groundwater or from general wear and tear causing scratches on the paint layer protecting the sensor, and issues during calibrations. DO concentrations in the reactive zone ranged from 0.55mg/L to 0.75 mg/L in Quarter 3, and 0.59mg/L to 0.84mg/L Quarter 4 monitoring. Although DO concentrations were detected above the 0.5 mg/L threshold for anaerobic conditions, other geochemical indicators suggest the reactive zone was in a reductive state. These indicators will be discussed in the subsequent sections.

~~4.5.34.6.3~~ Nitrate

Nitrate concentrations decrease under mild reducing conditions in groundwater and typically after DO is depleted to concentrations <0.5 mg/L. Nitrate results are shown in Table ~~106~~. During baseline monitoring on 14–16 September 2020, nitrate was below the reporting limit (<1.3 mg/L) at all wells in the reactive zone. Despite elevated DO in later Phase II monitoring events, nitrate

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concentrations remained non-detect, serving as one line of evidence that the reactive zone was in a reducing state for the remainder of Phase II monitoring.

4.5.44.6.4 Ferrous Iron

Ferrous iron species accumulate in the groundwater in strongly reducing environments. Elevated levels of ferrous iron, caused by the reduction of ferric iron, indicate that the groundwater environment is sufficiently reducing to sustain iron reduction. At this state, reductive dechlorination of highly chlorinated VOCs, such as PCE and TCE, may occur if competition from other electron acceptors is low. Concentrations of ferrous iron from Phase II are plotted in Appendix H (Figures H-5-0 through H-5-13) and summarized in Table 10 for the reactive zone wells.-

Baseline ferrous iron concentrations, measured in September 2020, were in the range of 0.0 mg/L to 2.0 mg/L in the reactive zone of the treatability study area. Only high-TCE wells S138A, S140A and S146A, and low-TCE well S139A, had detectable ferrous iron concentrations before injections. These wells were in the ROI of the Phase I injections, which indicates the former reactive zone continued to exhibit reducing conditions at the start of Phase II. The downgradient monitoring wells (S025A, S049A and S088A) and the background well (S134A) had no detectable ferrous iron during baseline monitoring.

Ferrous iron concentrations ranged from 0.5 mg/L to 5.0 mg/L in the reactive zone 30 days after injections. The downgradient monitoring wells (S025A, S049A and S088A) had detectable concentrations of ferrous iron, but ferrous iron was not detected in background well (S134A). Monitoring wells S138A, S140A, S146A, and S139A which had detectable ferrous iron during baseline monitoring, experienced a sharp increase in ferrous iron after injections, then dropped baseline or below baseline 30 days after injections. As mentioned earlier, these wells were in the Phase I reactive zone and still subject to reducing environment at the time of Phase II injections,

Ferrous iron concentrations increased after 30 days at the mid-range wells and low-TCE well S159A.

By 60 days after injections, ferrous iron ranged from 0.0 mg/L to 5.5 mg/L in the reactive zone. Of the wells that had detectable ferrous iron during baseline monitoring (S138A, S139A, S140A and S146A), wells S138A or S139A had no detectable ferrous iron during the Month 2 event, while S140A and S146A returned to baseline levels (0.5 mg/L and 1.0 mg/L, respectively).

Of the monitoring wells in the reactive zone, only S138A and S140A had lower ferrous iron concentrations than baseline levels as of Quarter 4 monitoring in November 2021. All other wells had increased above baseline ferrous iron concentrations.

~~4.5.5~~ 4.6.5 Sulfate and Sulfide

Sulfate is an alternate electron acceptor for microbial respiration in the absence of oxygen, nitrate, manganese, and ferric iron. Sulfate reduction typically occurs when the groundwater is at a highly reducing state and produces sulfide as a by-product. Depleted sulfate concentrations relative to baseline conditions indicate that the redox environment is sufficient for reductive dechlorination. Sulfate concentrations less than 20 mg/L are desirable but not required for reductive dechlorination of VOCs (EPA, Bioremediation Anaerobic Bioremediation (Direct), 2021). High levels of sulfate and the absence of carbon substrate (low TOC) may indicate that additional substrate is necessary to promote biodegradation. Concentrations of sulfate and sulfide from Phase II are plotted in Appendix H (Figures H-6-0 through H-6-13).

Sulfate levels in the reactive zone were comparable to up/downgradient wells during baseline monitoring with concentrations ranging from 130 mg/L to 240 mg/L at the up/downgradient wells, and sulfate in the reactive zone ranging from 110 mg/L to 190 mg/L. However, 30 days after injections, sulfate concentrations in the reactive zone decreased substantially (except for S160A), while the up/downgradient wells remained elevated. Sulfate concentrations at the low-TCE wells decreased to <20 mg/L after 30 days (1.0 mg/L at S137A; <5.0 mg/L at S139A; 6.8

mg/L at S159A). Of the mid-range wells, only S143A reached <20 mg/L after 30 days, while S141A decreased to 89 mg/L and S160A increased to 130mg/L. Sulfate concentrations decreased at the high-TCE wells but only wells S138A and S146A were <20 mg/L at 30 days post-injection. Sulfate concentrations remained very low at S138A, S158A and S159A during each post-injection monitoring event, including the final monitoring event in 8–10 November 2021, indicating that the strongest reducing conditions may be present at these wells. These wells also had the longest TOC retention times, shown in Figure 663. During the fourth quarter monitoring, sulfate concentrations were above 20 mg/L at all other wells in the reactive zone, and TOC was depleted indicating that additional substrate may be required to promote reductive dechlorination (EPA, Bioremediation Anaerobic Bioremediation (Direct), 2021).

Sulfide is a by-product of sulfate reduction and increases as sulfate decreases. Sulfide typically precipitates with iron minerals, but in absence of iron compounds, sulfide may accumulate and become toxic to dechlorinating bacteria. Sulfide concentrations were highest at S138A and S146A; however, sulfide does not appear to have affected DHC populations at these wells as concentrations remained above screening criteria through all of Phase II.

4.6.4.7 Dissolved Gases

4.6.4.7.1 Carbon Dioxide

Carbon dioxide is generated from the fermentation of the substrate carried out by microbes and utilized as an electron acceptor in the methanogenic process. It is a by-product of both aerobic and anerobic degradation. Elevated carbon dioxide above baseline concentrations indicate microbial activity has been stimulated (EPA, Bioremediation Anaerobic Bioremediation (Direct), 2021). The concentration of carbon dioxide over the performance period is shown in time series plots in Figures H-7-0 through H-7-11 (Appendix H) and summarized in Table 10, along with other key redox parameters for this evaluation.

Baseline concentrations of carbon dioxide detected in the treatability area ranged from 20.0 mg/L to 78.7 mg/L, with a median value of 27 mg/L. Following the injections, the median carbon dioxide concentration increased to 99.5 mg/L after 30 days (range of 23 mg/L to 284 mg/L in reactive zone). Table 10 shows Phase II carbon dioxide results and statistics.

Microbial activity appeared stimulated by injections during month 1 monitoring event; however, many wells in the reactive zone dropped back to baseline ~~conditions—carbon dioxide concentrations after~~ at 60 days. This phenomenon was observed at all high-TCE wells and at well S143A, the most western well in the reactive zone. The low-TCE wells and two of the mid-range wells (S141A and S160A) remained stable or increased slightly at 60 days.

Of the high-TCE wells, carbon dioxide concentrations indicate that the most microbial activity occurred at well S158A, where carbon dioxide reached a maximum of approximately 400 mg/L in the fourth quarter. Despite indicators such as VFA concentrations and TOC that implied substrate availability at mid-range TCE wells was poor, carbon dioxide concentrations continued to trend upward through the fourth quarter, with final concentrations of 219 mg/L, 140 mg/L and 271 mg/L at S141A, S143A and S160A, respectively. In the low-TCE wells, carbon dioxide peaked during the 60-day monitoring event at S159A (284 mg/L), and during the final monitoring event at S137A and S139A (155 mg/L and 121 mg/L, respectively).

The fourth quarter sampling results show carbon dioxide concentrations were above baseline conditions. The median carbon dioxide concentration during the fourth quarter was 147.5 mg/L, compared to 27 mg/L during baseline. This was the case for the wells inside the reactive zone, as well as for monitoring locations upgradient and downgradient (wells S134A and S049A). Carbon dioxide trends correlate with the levels of alkalinity observed across the study area, refer to, See plots in Appendix H plots of alkalinity (Figures H-11-0 through H-11-11).

4.6.24.7.2 Dissolved Hydrogen

Hydrogen is generated by fermentation of carbon substrate and is rapidly consumed by other bacteria, such as denitrifiers, iron-reducers, sulfate-reducers, methanogens, and dechlorinating microorganisms, such as DHC. These microbes consume available hydrogen at varying efficiencies, with the lower redox state bacteria being the most efficient and higher reducing conditions producing the least efficient hydrogen consumption rates. Therefore, it is possible to estimate the redox state of the groundwater, given the hydrogen concentration. Time series plots showing Phase II hydrogen concentrations are available in Appendix H (Figures H-8-0 through H-8-11).

At hydrogen concentrations less than 0.1 nmol/L (nM), hydrogen is consumed at a very efficient rate, and the redox state of the groundwater is at a denitrification state. Studies show that hydrogen concentrations from 0.2 – 0.8 nM indicate conditions are in the iron (III) reduction redox state; hydrogen of 1 – 4 nM indicate a sulfate reducing redox state; and hydrogen from 5 – 20 nM indicate methanogenesis (Air Force, 2007). Concentrations less than 2 nM may indicate that additional substrate may be required if TOC levels are depleted (EPA, Bioremediation Anaerobic Bioremediation (Direct), 2021).

Additionally, dechlorinating bacteria must successfully compete against other microorganisms that also make use of hydrogen. Existing guidance documents suggest that high sulfate levels may be problematic for reductive dechlorination of VOCs because the presence of elevated concentrations of sulfate can decrease the utilization of substrate for biotic dechlorination of chlorinated solvents (Air Force, 2007). However, the presence of sulfate does not preclude successful EAB applications, refer to Phase II sulfate concentrations in Section 4.6.5.

During baseline sampling, the median hydrogen concentration in the reactive zone was 1.65 nM (range of 0.61 nM to 53 nM), refer to Table 10 for hydrogen concentrations and statistics. After injections, the median hydrogen concentration increased to 5.6 nM after 30 days. The high-TCE

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wells in the center of the reactive zone (S138A, S146A and S158A) measured hydrogen concentrations of 210 nM, 120 nM and 64 nM, respectively, after 30 days, which were the greatest of Phase II. Hydrogen concentrations at the background well were below detection 30 days after injections (<0.49 nM at S134A). Background hydrogen increased to above 1mg/L after 60 days, and during the second and third quarter monitoring events.

During the 60 day and first quarter monitoring events, hydrogen concentrations were consistently below 2 nM at S139A and S160A. However, by the second quarter monitoring event in May 2021, hydrogen exceeded 2 nM at every well in the treatability study area, indicating that redox conditions were conducive to reductive dechlorination. Hydrogen concentrations in the high-VOC wells ranged from 3.9 – 14 nM, signifying a methanogenesis redox state at this time (Air Force, 2007). Hydrogen at the low-TCE wells and mid-range TCE wells ranged from 2.2 – 4.4 nM, signifying a sulfate reduction state during the second quarter. In Phase I, it was concluded that sulfate reduction was the dominant redox process in the Phase I treatability area (Locus Technologies, 2018).

After the second quarter, hydrogen concentrations trended downward, and during the fourth quarter monitoring event, only wells S138A and S158A were in the optimal range for reductive dechlorination. Well S159A was just below the optimal range. Additional substrate loading may be necessary to stimulate methanogenesis across much of the treatment zone since the desired threshold of 2 nM was not sustained.

~~4.6-34.7.3~~ 4.7.3 Methane, Ethane and Ethene

The measurement of dissolved gases such as methane, ethane and ethene in groundwater is an indication of bioremediation. Elevated levels of methane indicate fermentation is occurring in a highly reducing environment and that subsurface conditions are appropriate for reductive dechlorination. Concentrations of ethene and ethane at levels at least an order of magnitude greater than background levels is evidence of reductive dechlorination of VOCs. However, rapid

biodegradation of ethane and ethene often occurs, lowering concentrations of these non-toxic by-products. Time series plots showing Phase II methane, ethane and ethene concentrations are available in Appendix H (Figures H-9-0 through H-9-13).

The presence of methane above background conditions indicates methanogenesis is occurring and methane greater than 1.0 mg/L is desirable for biodegradation (EPA, Bioremediation Anaerobic Bioremediation (Direct), 2021). During baseline monitoring, methane groundwater concentrations were elevated to >1.0 mg/L at wells S137A, S139A, S146A and S160A, refer to - ~~Methane concentration plots are shown in Appendix H and statistics presented in Table 10 for~~ dissolved methane concentrations and statistics. The baseline concentration of methane ranged from 0.0035 mg/L to 8.1 mg/L in the reactive zone, and the background concentration at S134A was 0.031 mg/L. After injections, a total of seven wells in the reactive zone reached methane concentrations of at least 1 mg/L after 30 days, but wells S143A, S158A and S159A remained below 1 mg/L. The background methane concentration at S134A decreased from 0.031mg/L to 0.02mg/L after 30 days and remained below 1mg/L throughout the Phase II monitoring period.

In the second, third and fourth quarters, all reactive zone wells were above 1 mg/L except for wells S140A and S146A. Methane levels <1.0 mg/L and the accumulation of cis-DCE and vinyl chloride as seen in Table 9 may indicate that additional substrate or addressing other causes of stalling such as Freon 113 is required to shift reducing conditions into an environment suitable for reduction of these compounds. However, methane concentrations at S140A and S146A were still approximately an order of magnitude higher than background concentrations. Elevated methane concentrations (>1mg/L) were measured during the last three quarters at S049A, located immediately downgradient from the reactive zone; however, methane production was not evident at the adverse impact monitoring wells S025A and S088A, located farther downgradient.

Ethane and ethene are the final daughter products in the degradation of chlorinated ethanes and ethenes, respectively. Ethene production is discussed in depth in Section 4.5.2, along with the

other TCE daughter products. Concentrations of ethene and ethane at levels at least an order of magnitude greater than background levels is evidence of reductive dechlorination of VOCs. During Phase II, ethene increased from baseline (assumed equivalent to background) levels by over two orders of magnitude at wells S137A, S141A, S143A and S158A; by approximately one order of magnitude at S139A and S159A; and by less than one order of magnitude at S138A, S140A and S146A. Ethene concentrations decreased from baseline at well S160A.

Compared to baseline conditions, ethane increased by over two orders of magnitude at well S137A; by approximately one order of magnitude at S143A, S158A and S159A; and by less than one order of magnitude at S138A, S139A, S140A, S141A and S146A. Ethane also decreased from baseline at S160A. Ethane was less concentrated than ethene across the treatability study area.

4.74.8 Biological Activity

Biodegradation of VOCs involves specialized microorganisms and hospitable environments. *Dehalococcoides* (DHC) is the only known bacterial group capable of complete reductive dechlorination of PCE to ethene. Studies show that populations of DHC in the groundwater at concentrations greater than 1×10^4 cells/mL correspond to ethene production at both EAB and natural attenuation sites (Microbial Insights, 2021). This evaluation uses DHC as the indicator bacteria and concentrations $> 1 \times 10^4$ cells/mL as the screening criterion to identify areas of the reactive zone where bioremediation is predicted to proceed at generally useful rates. This is a more conservative screening threshold than what was stated in the Work Plan and used in the Phase I evaluation ($> 1 \times 10^3$ cells/mL), as recommended by recent studies and Microbial Insights laboratory guidance. Populations of DHC between 1×10^1 cells/mL and 1×10^4 cells/mL indicate that other site-specific subsurface conditions may be limiting reductive dechlorination and are associated with less ethene production (Microbial Insights, 2021).

Prior to Phase II, efforts were made to quantify native bacterial species in the treatability study area. The initial quantification took place in 2009, in which DHC bacteria population in wells

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S134A (upgradient), S049A (downgradient) and S145A (unsampled during Phase II) were found to be present but below the DHC screening criterion at 7.2×10^1 cells/mL, 8.9×10^2 cells/mL, and 1.2×10^2 cells/mL, respectively.

In October 2016 prior to Phase I injections, native DHC populations within the study area ranged from 1.0×10^0 cells/mL to 9.4×10^2 cells/mL (Locus Technologies, 2018). After Phase I injections, DHC populations increased in the Phase I treatability study area, and wells S137A, S138A and S139A exceeded the screening criterion of 1×10^4 cells/mL by the third quarter monitoring event in August 2017. Accordingly, ethene production was most pronounced in these wells. Between baseline and the fourth quarter, ethene concentrations increased from <0.2 µg/L to 220 µg/L (100,000%) at S137A, from 0.24 µg/L to 520 µg/L (200,000%) at S138A, and from <0.2 µg/L to 96 µg/L (48,000%) at S139A (refer to Table 9). Wells below the screening criterion produced less ethene. During Phase I, there was a correlation between DHC populations and ethene production.

4.7.14.8.1 Direct Measurement

During Phase II of the treatability study, samples were collected for microbial evaluation during the baseline, 90-day, Quarter 3 and Quarter 4 monitoring events at twelve groundwater wells (no microbial samples from downgradient wells S025A and S088A). Between Phase I and Phase II, DHC populations fell to below the screening criteria at all wells in the study area as indicated by Phase II baseline concentrations seen in the Appendix H plots (Figures H-10-0 through H-10-11). However, ethene concentrations remained elevated at most wells in the reactive zone.

After Phase II injections, DHC populations surpassed 1×10^4 cells/mL in the reactive zone (confirmed during the 90-day monitoring event), except for well S160A which barely met the target DHC. Upgradient and downgradient wells experienced negligible increases in DHC after 90 days. Despite S049A's proximity to the injections, DHC remained below 1×10^4 cells/mL through all post-injection monitoring events.

The highest DHC populations in Phase II were typically found in the high-TCE wells in the southern end of the study area. After injections, DHC concentrations were at least one order of magnitude above the DHC screening criterion of 1×10^4 cells/mL at wells S138A, S158A and S140A throughout Phase II. Accordingly, these wells produced the most ethene. The maximum DHC concentration was detected during the final monitoring event at S138A at over two orders of magnitude above the DHC screening criterion (1.2×10^6 cells/mL).

The mid-range and low-TCE wells, as well as S146A (high-TCE), exhibited concentrations around the DHC screening criterion of 1×10^4 cells/mL during most of Phase II. However, during the third quarter monitoring event, wells S159A and S160A fell below 1×10^4 cells/mL DHC and final DHC populations were 2×10^3 cells/mL and 4.7×10^3 cells/mL, respectively. This drop did not seem to affect the performance at S159A based on the VOC concentrations, however the lack of DHC and TOC at S160A indicates that not enough injection solution was present in the well.

During Phase II, functional genes produced by dechlorinating bacteria were also analyzed. VOC reductase genes provide a supporting line of evidence when evaluating the potential for accumulation of daughter products versus the potential for complete reductive dechlorination to ethene (Microbial Insights, 2021). The DHC strain functional genes evaluated include tceA reductase (abbreviated TCE, not to be confused with trichloroethene), Vinyl Chloride Reductase (VCR), and BAV1 Vinyl Chloride Reductase (BVC). These DHC functional genes encode reductive dehalogenases that dechlorinate TCE, cis-DCE and vinyl chloride. Refer to the microbial population plots in Appendix H (Figures H-10-0 through H-10-11).

The functional gene TCE indicates the potential for dechlorination of TCE, but the absence of TCE gene does not preclude the potential for reductive dechlorination. Populations of the TCE gene followed a similar geospatial trend to DHC, with the highest TCE genes typically found at the high-TCE wells, especially during the final two monitoring events. The up-gradient and down-

gradient wells, S134 and S049A, generated substantially fewer TCE genes than the wells in the reactive zone.

The functional gene VCR encodes a DHC reductase enzyme responsible for dechlorination of cis-DCE and vinyl chloride to ethene. The BVC gene encodes an enzyme that dechlorinates vinyl chloride to ethene. The absence of both VCR and BVC genes suggest vinyl chloride may accumulate (Microbial Insights, 2021). During Phase II, BVC was below detection in the treatability study area. The amount of VCR in reactive zone wells increased after injections. Like other microbial indicators have shown (DHC and TCE gene), VCR was lower in the up/down gradient wells, and this was true throughout Phase II. The lowest VCR populations in the reactive zone were found in well S146A, which was on the higher end of the spectrum for DHC and TCE genes. As seen in Table 9, Vinyl chloride rebounded at well S146A in the fourth quarter, cis-DCE remained elevated during Phase II .and TCE rebounded in the third quarter at this well. Because vinyl chloride has accumulated in other wells, the functional genes VCR and BVC do not appear to accurately reflect the site dechlorination conditions and are not recommended to be used in the future as indicator parameters.

4.7.24.8.2 pH and Alkalinity

While microbial populations can tolerate a wide pH range, a neutral pH of between 6 and 8 is most conducive to the microbial growth (Parsons, 2004). Fermentation of substrates to metabolic acids and hydrochloric acids during dechlorination may decrease the pH substantially in low-alkalinity groundwater environments; therefore, monitoring of pH and alkalinity is crucial in the treatability zone. Concentrations of alkalinity that remain at or below background in conjunction with pH above 5 indicates that additional buffering agent could be required to sustain high rates of anaerobic dechlorination (EPA, Bioremediation Anaerobic Bioremediation (Direct), 2021). Temporal plots showing trends in pH and total alkalinity are available in Appendix H (Figures H-11-0 through H-11-11).

Baseline total alkalinity at groundwater wells inside the reactive zone ranged between 350 mg/L and 690 mg/L (see as seen in Table 6). Fourth quarter alkalinity increased above baseline reactive zone wells except for S146A. Alkalinity increased most at wells S137A, S141A, S158A, and S159A. Alkalinity correlated with trends in carbon dioxide, see Appendix H plots and carbon dioxide discussion in Section 4.7.1.

Baseline pH values ranged from 6.60 – 7.12 in the reactive zone with the median pH of 6.95. During injections, the pH mostly decreased but then returned to nearly baseline levels through the remainder of Phase II. In the fourth quarter, the median pH in the reactive zone was 6.72, and pH values ranged from 6.44 – 7.20.

The buffering capacity of the reactive zone sustained pH levels within recommended values throughout the study. A slight increase in alkalinity was observed across the treatability area with the exception of high-TCE well S146A, which still maintained a pH above 6, thus microbial populations in the reactive zone had a conducive growth environment in terms of pH and alkalinity.

4.84.9 Freon 113 Concentrations

Quantification of the effectiveness of injections at promoting anaerobic degradation of Freon 113 in wells S140A and S141A is one of the Phase II objectives stated in Section 2. This section reviews trends in Freon 113 concentrations in these key wells, as well as monitoring locations across the expanded Phase II treatability study area. Refer to Appendix H plots (Figures H-2-14 through H-2-27 Freon 113 molar concentrations; Figures H-3-14 through H-3-27 show units of micrograms per liter) and the summary of key analytical results in Table 9.

During baseline monitoring, the background concentration of Freon 113 was non-detect (<2.0 µg/L at S134A) and was only detected at one downgradient well (S025A at a concentration of 5.1 µg/L). Freon 113 in the reactive zone was most concentrated in the high-TCE wells with concentrations of 1,500 µg/L at S158A, 2,000 µg/L at S138A and 4,300 µg/L at S146A. The next

highest Freon 113 concentration was observed at S141A (240 µg/L). The rest of the mid-range and low-TCE wells had Freon 113 concentrations less than 25 µg/L during baseline monitoring.

Freon 113 in all high-TCE wells remained elevated approximately 30 days after injections, while concentrations in the rest of the reactive zone decreased. At high-TCE wells S138A and S158A, Freon 113 increased by 80% and 93% after approximately 30 days following injections, respectively. Wells S138A and S158A increased once more during Month 2 monitoring approximately 60 days after injections (53% and 62%, respectively).

Approximately 90 days after injections, Freon 113 in the high-TCE wells decreased from Month 2 concentrations by 55%, 43%, 21% and 37% at the high-TCE wells S138A, S140A, S146A and S158A, respectively. For the next three quarterly monitoring events, Freon 113 concentrations continued to decline at wells S138A. Freon 113 concentrations rebounded at S158A during the fourth quarter (79 µg/L to 860 µg/L) but remained below baseline concentrations.

Approximately 360 days after injections, Freon 113 decreased to 630 µg/L at S140A but increased to 6,100 µg/L at S146A. Freon 113 degradation was least apparent at these high-TCE wells, with final Phase II Freon 113 concentrations above or near baseline conditions. Freon 113 inhibits reductive dechlorination by DHC (specifically *Dehalococcoides mccartyi*) in a concentration-dependent manner, causing cis-DCE stalls (Im J, 2019). During Phase I, high concentrations of Freon 113 at well S140A were attributed to stalling in cis-DCE degradation, as discussed in the Phase I evaluation report (Locus Technologies, 2018). Again during Phase II, cis-DCE stalled at S140A as well as S146A (refer to Section 4.5.2.3). High Freon 113 concentrations were likely a contributing factor in the stalling. Compared to Phase I baseline concentrations, cis-DCE increased by 96.3% and 1,248% at S140A and S146A, respectively, across the Phase I and Phase II monitoring periods.

Concentrations of Freon 113 remained non-detect or very low (<5.2 µg/L) in the downgradient and background wells throughout Phase II. Freon 113 at the low-TCE and mid-range TCE wells

trended downward throughout the Phase II monitoring period, except for mid-range well S141A, which experienced rebounding of Freon 113 during the second quarter increasing from 22 µg/L to 120 µg/L. Freon 113 concentrations decreased during the fourth quarter at S141A to 51 µg/L. From baseline to the fourth quarter, Freon 113 concentrations at wells S138A, S139A, S141A, S143A, S158A and S159A were reduced by 80%, >50%, 79%, >94%, 43% and >98%, respectively. Freon 113 concentrations at wells S137A, S140A and S160A were below the action level throughout Phase II monitoring. Only well S146A increased from baseline concentrations by approximately 42%.

~~4.9.4.10~~ Volatile Organic Carbon ~~Volatile Fatty Acids (VFAs)~~

~~4.9.1~~ Total Organic Carbon

~~TOC was discussed in Section 4.5 with regards to the retention time in the Phase II treatability study area.~~

~~4.9.2~~ Volatile Fatty Acids (VFAs)

Volatile fatty acids (VFAs) are produced during fermentation of the substrate. Elevated concentrations of VFAs indicate microbial activity and substrate distribution. Key VFAs monitored during Phase II include lactic acid, acetic acid, pentanoic acid, propionic acid, pyruvic acid, and butyric acid. Concentrations of VFAs greater than 10 mg/L to 20 mg/L indicate that sufficient levels of substrate is available for redox processes to proceed (EPA, Bioremediation Anaerobic Bioremediation (Direct), 2021). Insufficient VFA concentrations imply additional substrate is required. Plots of VFAs are available in Appendix H (Figures H-12-0 through H-12-11),⁷ shown with the lower VFA threshold of 10 mg/L.⁷

Acetic acid was the most prevalent VFA produced in the reactive zone. During baseline monitoring, acetic acid was present but in low concentrations in all wells in the reactive zone (0.31 mg/L to 3.6 mg/L), as well as at the upgradient and downgradient wells (range of 0.3 mg/L

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to 0.41 mg/L). One month after injections, acetic acid concentrations increased to >20 mg/L at all wells in the reactive zone except wells S141A and S160A (well S141A was within the lower end of VFA threshold at 12 mg/L). Through the fourth quarter, acetic acid concentrations remained greater than 20 mg/L at wells S138A and S158A, and above 10 mg/L at S159A. There is correlation between acetic acid concentrations and TOC retention times, in which the lowest TOC retention times and acetic acid concentrations are found at S141A and S160A, while the highest TOC retentions and acetic acid concentrations are at wells S138A, S158A and S159A.

Lactic acid was the only VFA at S160A to breach 10 mg/L, which occurred during the fourth quarter (<0.53 mg/L to 17 mg/L). Similarly, during the fourth quarter, lactic acid concentrations increased from below detection (<0.53mg/L) to above the VFA threshold of 10 mg/L at wells S139A, S140A, S141A, S143A, and S158A.

Other VFAs monitored in Phase II only surpassed the VFA concentration threshold at a few high-performing wells in the reactive zone. Butyric acid exceeded 10 mg/L only at wells S158A and S159A. Concentrations of pentanoic acid, propionic acid and pyruvic acid exceeded 10 mg/L only at well S159A, which is the only monitoring location to achieve complete reductive dechlorination of VOCs to below action levels (refer to VOC concentrations at low-TCE wells Section 4.5.2.1). Thus, acetic acid seems to be the most useful VFA indicator for this injection solution and site, and the collection and evaluation of other VFAs is not recommended for future evaluations.

~~4.104.11~~ 4.104.11 Adverse Condition Monitoring

Wells in the area of the EAB treatability study area were monitored for adverse conditions that may inadvertently be caused by the introduction of EAB products in the subsurface. Monitoring and sampling ~~was~~were conducted using Table 4 of the Work Plan. This evaluation was limited to two metals which can be released under reducing conditions, manganese and arsenic. This discussion also addresses potential EAB induced VOC increases outside the Phase II reactive zone.

Concentrations of manganese and arsenic were compared upgradient of the study area, within the study area, and within two wells downgradient of the study area, S025A and S088A. As previously discussed, arsenic and manganese laboratory methods changed to dissolved analysis second quarter 2021 after it was discovered that total metals were erroneously collected and analyzed from baseline through first quarter. However, because total metal concentrations represent the dissolved (soluble) and particulate (insoluble) states, it is more conservative and will still be used in conjunction with dissolved metals for this analysis.

4.10.14.11.1 Manganese

Manganese monitoring data are presented in Table 4 and plotted in Appendix H (Figures H-13-0 through H-13-13). Manganese concentrations in upgradient well S134A, which represents background conditions for this study, were relatively stable or slightly decreasing concentration with an average around 450 µg/L. Within the treatment area, manganese concentrations increased after injections, then decreased or remained stable during the performance monitoring period. For example, well S138A located in the middle of the Phase II treatment area (also within the Phase I treatment area) (Figure 2), increased from a baseline concentration of 340 µg/L to 1800 µg/L 90 days after injections and remained elevated above baseline through the performance monitoring period. Well S158A, a well located on the north end of the Phase II treatment area, and newly installed for this phase, exhibited an increase in manganese concentrations through the third quarter (14,000 µg/L) then decreased fourth quarter. Thus, as expected, manganese concentrations increased in response to the injection solution in the Phase II treatability study area.

Well S049A, located approximately 40 feet downgradient of the Phase II treatability area, had a slight increase in manganese approximately 180 days after injections, then decreased to below baseline levels. Well S088A, located approximately 120 ft downgradient of the Phase II treatability area, did not demonstrate an increase in manganese concentrations. Well S025A, which is 364

feet downgradient of the Phase II treatability area, also did not demonstrate an increase in manganese concentrations. Both wells slightly decreased in concentrations over the Phase II monitoring, similar to the background well. Because wells furthest downgradient of the treatment area did not exhibit an increase in manganese concentrations, this indicates the impacts of the injection solution largely remain around the treatment area and are not creating an adverse condition with respect to manganese outside the area.

4.10.24.11.2 Arsenic

Arsenic monitoring data are presented in Table 6 and plotted in Appendix H (Figures H-13-0 through H-13-13). Because of non-detect results with elevated laboratory reporting limits, comparisons against baseline arsenic concentrations could not be made with certainty. Non-detect results were also reported periodically in various wells throughout the performance monitoring period. Thus, evaluations for arsenic impacts are limited to comparisons against background.

Arsenic concentrations in the upgradient background well S134A were non-detect or estimated around 8–10, approximately 90–270 days after injections. The highest arsenic concentrations within the treatability area ~~was~~^{were} noted in wells S139A, with a maximum arsenic concentration of 63 µg/L. Wells S137A, S140A, S143A, S146A, S158A, S159A, and S160A also exhibited arsenic concentrations above background from an estimated 15 µg/L – 21 µg/L. Well S049A, just downgradient of the treatability study area was non-detect for most events with two estimated concentrations of no more than 12 µg/L. Downgradient wells S025A and S088A post-injection concentrations were non-detect with reporting limits between 4.4–19 µg/L.

Because of the elevated reporting limit at the baseline event, it is not clear whether arsenic concentrations increased in response to injections in the Phase II treatability study area. Arsenic in some wells did increase, however concentrations are do not show an upward trend at the end of monitoring as seen in the Appendix H plots. This indicates arsenic will not be continually

generated at the treatment zone. Increases were not observed at the two wells furthest downgradient of the treatability study area, thus, adverse arsenic conditions are not being created by the EAB injections.

4.10.34.11.3 VOCs

Degradation by-products (daughter products) are generated as a result of EAB as discussed in Section 4.5. Cis-DCE and vinyl chloride in particular were generated within the reactive zone, sometimes resulting in concentrations higher than their baseline and action levels. This discussion focuses on potential impact of EAB daughter products downgradient of the Phase II reactive zone. Appendix H Figures H-2-0 through H-2-13 show VOCs in terms of moles per liter and Figures H-3-0 through H-3-13 show VOCs in terms of micrograms per liter.

Wells S049A, S088A, and S025A monitor groundwater downgradient of the Phase II reactive zone. As seen in the Appendix H VOC plots, Figures H-2-0 through H-2-13 show VOCs in terms of moles per liter and Figures H-3-0 through H-3-13 show VOCs in terms of micrograms per liter. At well S049A, which is located approximately 40 feet downgradient of the reactive zone, cis-DCE and vinyl chloride peaked during the second quarter monitoring event at approximately 180 days after injections. By the fourth quarter, vinyl chloride and cis-DCE decreased to below Phase II baseline concentrations but remained above action levels. The peak in daughter products at well S049A demonstrates that reductive dechlorination was likely stimulated as a result of injections.

The other two downgradient monitoring locations are located farther away from the reactive zone and were not directly impacted by Phase II injections. At well S088A, which is approximately 120 feet downgradient, daughter products remained relatively stable until the fourth quarter monitoring event when cis-DCE, vinyl chloride and ethene increased. This may indicate that EAB daughter products migrated to a distance of 120 feet after 360 days following injections. At S025A, which is 364 feet downgradient of the reactive zone, the detection of migrating daughter

products is unclear. Vinyl chloride increased 30 days after injections, then decreased to below baseline concentration approximately 180 days after injections, and vinyl chloride increased in the fourth quarter. Cis-DCE increased 180 days after injections and decreased in the fourth quarter.

In summary, an increase in daughter product concentrations at S088A during the fourth quarter monitoring event may indicate that EAB daughter products migrated to a distance of 120 feet 360 days after injections.

4.11.4.12 Soil Vapor Methane Monitoring

The results of the soil vapor well sampling events are presented in Table 7. Copies the analytical reports from the soil vapor sampling events are included in Appendix F.

4.11.4.12.1 Evaluation Criteria

Methane results from the soil vapor wells were screened against the same criteria as was groundwater well-head methane vapor: 10% of methane's LEL, which is 5,000 ppm. If methane was detected in concentrations lower than 5,000 ppm at the soil vapor wells, it suggested that the elevated methane concentrations detected in groundwater and well-head vapor were laterally constrained to the Phase II Treatability study area and that methane was attenuating before reaching nearby receptors. However, if methane is detected in concentrations greater than 5,000 ppm at the soil vapor wells, it provided a line of evidence that elevated methane concentrations in soil vapor extended laterally beyond the Phase II Treatability Study Area. This scenario would present potential health and safety issues for the occupants of both 815 Stewart Drive and 440 Wolfe Road as well as the field staff present on-site during groundwater and soil vapor monitoring activities. As such, the table below outlines the ~~actions—established~~actions established for methane screening criteria.

Soil Vapor Well Methane Concentration Criteria	Action
<10% LEL (5,000 ppm) in soil vapor wells	<ul style="list-style-type: none"> Continue monitoring soil gas wells near receptors at the frequency specified by the well head and groundwater methane concentration results Monitor soil vapor wells for oxygen
>10% LEL (5,000 ppm) in soil gas wells	<ul style="list-style-type: none"> Notify EPA Venting and/or mitigation Monitor soil vapor wells for oxygen

4.11.24.12.2 Helium Results

To evaluate if soil vapor samples have become diluted by ambient air during the sample collection process, Locus collected samples under a helium gas shroud. In general, a detection of helium suggests that some degree of leaking occurred during sample collection. Per the 2015 DTSC and RWQCB guidance, an ambient air leak of 5% is acceptable for the purposes of data evaluation in active soil gas investigations. The leakage ratio is obtained using the following expression:

$$\text{Estimated Leak Ratio (\%)} = \frac{[\text{Concentration of Helium in Sample (\%)}]}{[\text{Mean Concentration of Helium in Shroud (\%)}]} \times 100$$

Helium was detected in three regular field samples and one field blank sample. The leakage ratio was under 5% for the field samples, indicating they are within quality control limits and the data can still be used reliably for decision-making purposes. The detection of helium in the field blank most likely suggests a leak in the connection between the summa canister collecting the blank sample and the 1-liter Tedlar bag of nitrogen blank gas. Since this issue is constrained to a particular fastener in the blank sample train, this helium detection does not impact the data quality from this 8 June 2021 sampling event.

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4.11.34.12.3 Methane Results

Methane was not detected at any of the vapor well locations, except on one occasion at a concentration of 8900 ppm in SGI003A, on 17 July 2021. This anomalous result at SGI003A, however, is likely explained by the high methane recovery that the laboratory observed for the entire analytical batch. Furthermore, methane was not detected by the field instrument immediately following sample collection at SGI003A during this event, nor was it detected in the adjacent deeper implant, SGI003B, at the lab or in the field. Locus resampled both SGI003A and SGI003B on 6 August 2021 for confirmation and methane was not detected in either well.

4.11.44.12.4 Soil Vapor Monitoring Conclusions

Seven complete monthly soil vapor sampling events were conducted from February to July 2021 and one confirmation sampling event in August 2021. Over this period, methane was not detected in the soil vapor wells, except for one instance at SGI003A in which there was a laboratory discrepancy. Moreover, the confirmation resampling event at SGI003A and SGI003B, just over three weeks later, confirmed that methane was below detection. On this basis, the data strongly suggests that any biogenic methane generated as a result of anerobic bacteria activity during the Phase II Study was laterally constrained to the treatability study area and had attenuated before reaching nearby receptors. Thus, a hazard to workers, buildings, or its receptors was not present during the EAB Phase II performance cycle.

5 Additional Limited Groundwater Velocity Investigation

Over the course of the post-injection groundwater monitoring program, it was observed that concentrations of TOC, which is an indicator of SRS-SD substrate distribution, varied significantly from location to location. As discussed in Section 4.4.14.44.5 and seen in Figure 65, there were certain locations, such as S141A and S160A, wherein TOC was detected below the ideal concentration of 20 mg/L or greater, after a period of just one month or less following the injections. On the other hand, there were wells such as S138A, S158A, and S159A, in which TOC

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concentrations remained above 20 mg/L for the entirety of the post-injection monitoring period. The substrate distribution ultimately affected the performance of the EAB as discussed in Section 4.5.

Given this high variability in TOC distribution amongst wells that are clustered relatively close to one another, it is hypothesized that the local hydrogeologic conditions and small-scale variability within the Phase II study area may have influenced TOC retention. That is, a zone or multiple zones of preferential groundwater flow within the Phase II study area A-aquifer would provide a potential explanation as to why SRS-SD substrate was depleted at some locations, and not at others. Thus, a limited groundwater velocity investigation was developed and proposed to the EPA on 18 October 2021 via email, as a supplemental effort to the approved Work Plan for the Phase II study. The scope included monitoring of several Phase II study area wells at different depths.—Lithologies from boring logs were reviewed as the basis for monitoring depth and permeable layers identified.

After initial rescheduling due to equipment availability, the investigation was conducted from 10 to 14 January 2022. In addition, not all wells were investigated as originally planned because of equipment limitations. Further details are discussed in the below sections.

5.1 Hydraulic Influences on Phase II Study Area

There are two known external factors that would likely influence any potential preferential groundwater flow in the local subsurface of the Phase II study area. First, there is an actively operating basement dewatering sump at the 440 Wolfe Road property, to the northwest. Figure 2 shows the sump, 440S, in relation to the Phase II study as well as 2020 groundwater contours. This sump continuously operates with a flow rate of approximately 50 ~~gpm, and gpm~~ and has a significant influence on groundwater elevations in the area, as shown by the contours in Figure 2. The direction of groundwater is northwest towards the sump in much of the study area.

In addition to the 440 Wolfe sump, two trenches exist within the Phase II study area that partially coincide with the injection depths, which range from 15 to 36 ft-bgs. One trench is a former utility trench that runs northwest-southeast on the eastern side of the Phase II study area as seen in Figure 5, installed at an estimated depth of 7 to 9 ft-bgs. Per the original drawings, this trench was backfilled with aggregate base Class II backfill, which is predominantly gravel grains up to 0.75 inches in diameter (Emcon, 1984). The other trench is the former 811 Arques extraction trench, which runs east-west through the northern portion of the Phase II study area. This former extraction trench was installed to a maximum depth of 24 ft-bgs and extends 80 feet in length. This trench was backfilled with 10 inches of 0.75-inch diameter pea gravel (Emcon, 1984).

5.2 Investigation Methods

These high permeability lithologies within the Phase II study area combined with the hydraulic influence of the 440 sump present conditions that could contribute to possible preferential groundwater flow away from the Phase II study area. Between 10 to 14 January 2022, a limited investigation was implemented utilizing a Geotech Colloidal Borescope instrument to characterize groundwater flow velocity and direction at wells within and adjacent to the Phase II study area. The Colloidal Borescope is a down-well instrument that uses magnified imagery and a compass sensor to track moving particles suspended in the water column and determine horizontal velocity and trajectory of flow in real-time (Geotech, 2021). The Colloidal Borescope's specifications state it can observe flow at a pore scale and measures velocities ranging from 0 to 30 mm/sec (30,000 $\mu\text{m}/\text{sec}$ or ~8500 feet/day), although Geotech indicated that velocities greater than ~200 $\mu\text{m}/\text{sec}$ are ideal for obtaining useful data within a reasonable time frame. Real-time measurements are seen and recorded in Geotech's AquaLITE program.

At each well, different depths within the screen interval were monitored to test for consistent flow patterns. Generally, a consistent flow pattern is identified when particles are flowing with a stable average velocity and direction over the course of 10 to 15 minutes. This period gives the

suspended particles in the well time to settle after lowering the instrument down and flow patterns, if present, to emerge. A low permeable skin surrounding the well screen will result in groundwater flowing around the well and swirling flow within the well. Swirling can be identified by the flow of particles abruptly changing in velocity and direction for an extended period. In this way, the real-time readings inform the depths at which reliable data could be collected in each well. Although the well construction logs were used to identify high permeability lithologies within each screen interval, multiple depths were monitored at well to identify potential high permeability lenses within the beds of predominantly clay and silt.

To ensure proper particle tracking, instrument parameters required adjustment from location to location, and sometimes from depth to depth. These parameter adjustments were generally contingent on the turbidity of groundwater. Specifically, the following parameters required adjustment: particle size, particle sensitivity, capture rate, maximum particle speed, and minimum number of particle matches for vector determination. Once the tracking screen in AquaLITE visually mirrored that of the actual camera feed, it could be determined that particles were being accurately tracked.

If a consistent flow pattern was observed at a well at a particular monitoring depth for 10 to 15 minutes, a new AquaLITE file was created, and data was collected at that depth for roughly one hour. The table below details the dates on which each well was monitored.

Date	Velocity Monitoring Locations
1/10/2022	S142A, S143A, S159A, S160A
1/11/2022	S134B1, S140A, S160A
1/12/2022	S138A, S139A, S141A, S142A, S158A
1/13/2022	S049A, S137A, S146A, S158A, S159A

5.3 Groundwater Velocity Investigation Results

Groundwater velocity at most locations and at most depths could not be measured as originally planned within the timeframe of the investigation. As mentioned earlier, the ideal borescope velocity for stabilization within an hour time frame is approximately 200 $\mu\text{m}/\text{sec}$. However, the most recent estimate of groundwater seepage velocity within the Phase II study area, used for the design of substrate volumes, was 0.03 ft/day (0.106 $\mu\text{m}/\text{sec}$). (Locus Technologies, 2020). For the borescope to accurately measure particle velocities of 0.03 ft/day, a monitoring period of hours and possibly even days would be required. Thus, the borescope was used to identify and record consistent flow patterns at discrete depths in each well that deviated from the expected low flow conditions. The depths at which consistently higher groundwater velocities were detected were then examined as potential preferential groundwater flow zones.

Monitoring data was collected after consistent flow patterns were observed at the three following wells: S138A, S141A, and S158A. At S138A, data was collected at 14 ft-bgs and 20 ft-bgs. At S141A, 16.8 ft-bgs and 22 ft-bgs. At S158A, data was collected at 16 ft-bgs. Copies of the monitoring summaries from each location and depth are presented in Appendix I.

5.3.1 Data Usage and Interpretation

The Colloidal Borescope utilizes vector-based analysis to determine the true direction and velocity of particle flow. The vector-based values are slightly different than an overall average of all each measured quantity. This is because taking the average of vector data requires consideration of both the direction and the magnitude of velocity. For instance, if a particle is moving due north at 200 $\mu\text{m}/\text{s}$ and a second particle is moving due south at 100 $\mu\text{m}/\text{s}$, a simple average of the velocities and directions would yield a velocity of 150 $\mu\text{m}/\text{s}$ in the due east direction. However, a vector-valued average result also includes the influence of the magnitude of velocity and, in this case, would yield a flow rate of 100 $\mu\text{m}/\text{s}$ in a due north direction. In nearly

all cases, the vector-based determination of net flow is the most accurate way to determine velocity and direction over a monitoring (Geotech, 2021). As such, groundwater flow will be reported and discussed based on averages derived from vector analysis.

5.3.2 S138A Results

The average measured groundwater velocity in S138A at 14 ft-bgs was 179.59 $\mu\text{m/s}$, or 50.91 ft/day, with an average flow direction of 61.66° (northeast). The values for this depth were calculated based on 3650 observations collected over a 64-minute monitoring period on 14 January 2022. At 20 ft-bgs, the average ~~flowrate~~ velocity was 198.35 $\mu\text{m/s}$, or 56.23 ft/day, in the average direction of 70.73° (east northeast). Over a 62-minute monitoring period on 14 January 2022, 3579 observations were collected for this 20 ft-bgs monitoring depth. The soil at 14 ft-bgs was logged as clayey sand (SC), comprised of 50% fine to coarse sand and 10% gravel. At 20 ft-bgs, the soil type was sandy clay (CL), with 35% fine to coarse sand, 5% gravel, and extensive rootlet networks.

At both depths, the velocity of suspended particles remained stable for the entire monitoring period. This suggests that the initial disturbance caused by placing the borescope at the monitoring depths had subsided and the flow of particles was not due to external disturbances. There was, however, some variability in flow direction during the monitoring periods for both depths. In both cases, flow direction oscillated from roughly 30° to 90° on 10-minute intervals, see Appendix I. Given this oscillation, there is a lower degree of certainty that the velocity and flow direction is reliable.

5.3.3 S141A Results

The average measured groundwater velocity in S141A at 16.8 ft-bgs was 159.18 $\mu\text{m/s}$, or 45.12 ft/day, with an average flow direction of 340.69° (north northwest). The values for this depth were calculated based on 392 observations collected over a 56-minute monitoring period on 12 January 2022. At 22 ft-bgs, the average flowrate was 238.91 $\mu\text{m/s}$, or 67.72 ft/day, in the

average direction of 340.29° (north northwest). Over a 11-minute monitoring period on 14 January 2022, 299 observations were collected for this 22 ft-bgs monitoring depth. This monitoring period was limited by time constraints on the final monitoring day. The soil at 16.8 ft-bgs was logged as sand to silty sand (SP-SM), comprised of 80% fine to coarse sand and 10% gravel. At the 22 ft-bgs depth, the borescope was set at the approximate contact between a clay (CL) lithology with just 5% fine to coarse sand and a sandy clay (CL) bed containing 40% fine to coarse sand and trace gravel.

As compared to the monitoring conditions at both S138A and S158A, groundwater in S141A was significantly less turbid. This is reflected in the lower particle counts and is supported by turbidity measurements taken at S141A during the Quarter 4 sampling event, in which turbidity never exceeded 0.9 NTU. At both monitoring depths, the flow direction of suspended particles remained stable in the northwest direction for the entire monitoring period. This suggests that the measured flow of particles was not due to external disturbances. At the 16.8 ft-bgs monitoring depth, velocity measurements were relatively stable around the mean. At the 22 ft-bgs monitoring depth there was, however, a 1-minute spike in flow velocity that corresponds with a change in flow direction from northwest to southeast. This anomaly likely biases high the flow velocity. Immediately after the disturbance, the velocity and flow direction stabilized to the flow pattern of northwest flow velocity of roughly 200 $\mu\text{m/s}$ that was observed prior to initiating the monitoring period at 22 ft-bgs. A longer monitoring period at this depth would have likely sustained this trend.

5.3.4 S158A Results

The average measured groundwater velocity in S158A at 16 ft-bgs was 37.90 $\mu\text{m/s}$, or 10.74 ft/day, with an average flow direction of 147.0161.66° (northeast-south southeast).—These results are based on 3698 observations collected over a 77-minute period on 13 January 2022.— The soil at 16 ft-bgs was logged as sand to poorly graded sand with silt (SP-SM). Approximately

10 minutes after beginning the monitoring period, the measured velocity and direction of flow started exhibit random behavior. These random shifts in direction and magnitude of velocity lasted for the duration of the monitoring period, indicating the borescope was likely measuring swirling flow within the well caused by impermeable lithologies at the probe depth. Thus, this data cannot be treated as reliable.

5.3.5 Discussion of Velocity Results

The average flow direction and velocity of groundwater in S138A at both monitoring depths was very consistent: 50.91 ft/day towards 61.66° (northeast) at 14 ft-bgs and 56.23 ft/day towards 70.73° (east northeast) at 20 ft-bgs. This strong observed trend towards the northeast at both depths exaggerates the slight eastward deviation from due north in regional groundwater flow represented in Figure 2 of Locus' the 2020 Groundwater Monitoring Report (Locus Technologies, 2021). Per the report, the A-aquifer regional groundwater flow bearing trends at around 15° degrees (north northeast) near the Phase II study area (excluding the impact of the 440 sump). While the direction of flow at S138A is not completely consistent with regional groundwater flow, it is possible that within certain high permeability lithologies in the Phase II study area, groundwater flow trends slightly more eastward than previously estimated. More highly resolved groundwater elevation data within the Phase II study area would potentially augment this finding. For purposes of this study, the groundwater flow results are determined to be uncertain and thus neither the groundwater flow or nor velocity should be used to form conclusions.

158A flow monitoring exhibited random shifts in direction and magnitude of velocity that lasted for the duration of the monitoring period, indicating the borescope was likely measuring swirling flow within the well caused by impermeable lithologies at the probe depth. Thus, this data cannot be treated as reliable, and it should not be used to form conclusions.

In S141A, the average flow direction at both monitoring depths was remarkably similar, although flow velocities were slightly different: 45.12 ft/day towards 340.69° (north northwest) at 16.8 ft–

bgs and 67.72 ft/day towards 340.29° (north northwest) at 22 ft-bgs. Both monitoring depths are generally consistent with the 2020 Groundwater Monitoring Report groundwater flow direction and are within the injection depth range of 15 to 36 ft-bgs. Similarly, both 16.8 and 22 ft-bgs could be depths consistent with the nearby former 811 extraction trench depth. The true depth of the trench's pea gravel backfill remains uncertain as the ground surface has changed since the trench was originally installed, but the depth to bottom measured in the field at the former sump access point was 20.40 ft-bgs. This depth could potentially coincide with one or both monitoring depths at S141A, providing a high permeability zone for groundwater to preferentially flow away from Phase II study area.

Based on the wells measured in this investigation, S141A was the sole well with reliable data, with a velocity that ranged from 45.12 to 67.72 ft/day and a direction of around 340° (north northwest). These velocities constitute a marked difference from the estimated Phase II study area seepage velocity of 0.03 ft/day calculated in the Work plan-PlanWorkplan (Locus, 2020). At each monitoring depth, the lithology corresponded well with the measured flow. That is, the proportion of coarse-grained sediments in the soil type would be sufficient for allowing enhanced groundwater flow at each monitoring depth. As such, the presence of these detected zones of higher groundwater flow provides a line of evidence to suggest that there is heterogeneous velocity and direction of groundwater flow within the Phase II study area.

As another measure of groundwater velocity in the vicinity of the Phase II study area, the presence of substrate material was observed in sediment filters handling water from the 440 Wolfe basement sump. The material was detected within eight days after the first injection activities on 10 November 2020, when it reached sufficient concentration to clog the filters. Based on this observation, the substrate likely initially reached the sump within less than eight days. Based on the distance and direction from the injection area to this sump (approximately 290 feet, 315° northwest), the calculated average groundwater velocity to reach the sump in eight days is 36

ft/day. If the substrate arrived within six days of injection, the calculated velocity would be 48 ft/day. This calculated value is reasonably consistent with range directly measured in S141A (45–68 ft/day), suggesting that these velocities are representative, at least for the area northwest of the Phase II study area.

In summary, the presence of multiple elevated groundwater velocity flow zones in the direction of the 440 Wolfe Sump at S141A likely account for the rapid loss of TOC observed during the post-injection monitoring period. It also provides insights as why the same poor TOC retention may have occurred at other wells within the Phase II study area. Additionally, the unexpected direction of flow at multiple depths in S138A, underscores the need for better understanding of the hydrogeologic conditions underlying the Phase II study area.

6 Summary of Results

Phase II of the Signetics EAB treatability study was conducted from September 2020 to November 2021. Radius of influence, delivery techniques, TOC retention time, COCs, and multiple other performance indicator parameters were monitored as part of the effort as discussed in detail in Section 4. This section summarizes the EAB performance by reviewing monitoring results in each well for a selected number of parameters as seen in Table 11. Wells are discussed by baseline TCE concentrations groups: low, ~~medium~~ mid-range, and high. TCE wells (refer to Section 4.2.1).

6.1 Low-TCE Wells

S159A well monitoring results indicated successful EAB performance overall. All key VOCs were reduced to below action levels. This is attributed to a TOC retention time of four quarters which enabled reducing conditions and dissolved gas production. While DHC populations dropped just below the performance criteria in the third quarter, the population was sufficient enough to continue reductive dechlorination. This well was located 10 ft cross gradient of INJ-4. The

injection was delivered via the TDIP tool using an injection solution with the standard ratio (84 gallons SRS-SD, 3.5 liters TSI-DC, 78 pounds sodium bicarbonate, and 4599 gallons of conditioned water) at a pressure of 170 PSI.

Well S137A monitoring results indicate successful TCE reduction to acceptable levels—Cis-DCE and vinyl chloride decreased as well, however rebounded in the second and fourth quarter, respectively. Well S139A initially had TCE, cis-DCE, and vinyl chloride reductions, however they all rebounded 60 days post-injection. The TOC retention time in both these wells was only 90 days, and sulfate reducing conditions rebounded in the quarters soon afterwards. During injections, the maximum TOC concentration in S137A, however was 520 mg/L when compared to 190 mg/L in S139A although the injection solution was the same.—This greater TOC concentration contributed to a better reduction in TCE in S137A. Despite this small success, cis-DCE and vinyl chloride rebounded in both wells indicating not enough substrate was available to sustain anaerobic treatment. Additional substrate is likely needed in the area of these wells to continue degradation and complete the degradation pathway.

Freon 113 was reduced or did not change in these low-TCE wells, wells; however baseline concentrations were below levels of concern.

6.2 Mid-range TCE Wells

Well S143A, located on the west side of the Phase II reactive zone near INJ- 10, had significant TCE and cis-DCE decreases, however rebound occurred in the second quarter. Vinyl chloride also rebounded above the baseline in the same quarter. Biotic degradation was apparent by the increased ethene and methane production, as well as a DHC population at target level. Despite these indicators, the TOC retention time in this well was two quarters, and sulfate reducing conditions rebounded in the same quarter. This indicates that not enough substrate was available to sustain anaerobic treatment. During injections, the water level increased by 1.25 ft, lower than other wells with similar distances from the injection point, indicating less impact from the

injection. Additional substrate is likely needed in the area of this well to continue degradation and complete the degradation pathway.

Well S141A and S160A, located on the northwest side of the reactive zone, had limited VOC reductions and resulted in a slight increase to cis-DCE and vinyl chloride levels in S141A. The TOC retention time in both these wells was less than 7 days and sulfate reducing conditions did not decrease to the desired 20 mg/L level. This indicates not enough substrate was available to sustain anaerobic treatment. The additional groundwater velocity investigation pointed to a higher than expected velocity in well S141A, over 45 ft/day compared with the 0.03 ft/day estimated during the substrate design (Locus Technologies, 2021). Based on additional lines of evidence, including nearby trenches that may serve as potential preferential pathways and the date when sediment filters from the 440 Wolfe basement sump were impacted with substrate, it is likely that the operation of the sump impacted the distribution of the injection solution at this location and other wells nearby (i.e. S139A and S160A). Thus, the design as proposed should be modified to account for potential hydraulic influences. A permeable reactive barrier or a recirculating system may be more appropriate if the 440 Wolfe sump continues to operate. Hydrogeological properties may also need to be further investigated as a basis of design.

Freon 113 was reduced or did not change in the mid-range TCE wells, wells; however baseline concentrations were below levels of concern.

6.3 High TCE Ww wells

S138A is located near the center of the Phase II reactive zone and was also included in the Phase I reactive zone. TCE was reduced by 99.9%, from 6,800 to 6800 –10 µg/L. Cis-DCE was also initially reduced from 25,000 to– 1,900 µg/L however rebounded in the second quarter. Vinyl chloride steadily Vinyl chloride increased increased from Phase II baseline through to the second quarter, decreased in the third quarter and rebounded to 2,000 µg/L –and was above Phase I baseline levels at the conclusion of Phase II monitoring. Compared to baseline conditions

measured in Phase I, vinyl chloride increased over 2,00% over the course of Phase II. Freon 113 is present in relatively high concentrations in this well and also rebounded after some reduction. While rebounding occurred, trends still indicate reductive dechlorination is occurring at this well. The TOC retention time at this well S138A was four quarters, indicating substrate is still available to sustain anaerobic treatment. Additional SRS-SD was applied in the injection solution (140 pounds instead of 84), indicating the increase in SRS-SD sustained adequate TOC levels when compared to other monitoring locations with high levels of TOC. However, according to the SRS-SD vendor, Terra Systems, 1–3 years of TOC retention time is common at their sites, therefore additional substrate may be needed to address higher levels of COCSCOCs. Further monitoring is recommended to see if the remaining substrate may continue to aid in degradation. Otherwise, rebound may be due to a factor other than the lack of substrate. It should be noted that an oscillation in water levels was observed in the first two hours of injection. This oscillation was unique to S138A and could be indicative of a compromised well screen or casing. Further investigation of the well condition is recommended.

S140A exhibited the highest baseline concentrations of TCE, cis-DCE, and vinyl chloride within the Phase II treatability study area. Well S140A was also within the Phase I reactive zone. TCE reductions after the injection of INJ-8 were strong and concentrations decreased from 15,000 to <200 µg/L. The reporting limit for TCE was elevated because cis-DCE concentrations were high enough to cause interference. Samples were subsequently diluted by the laboratory, elevating the reporting limit of VOCs above levels needed to adequately assess performance. Cis-DCE concentrations have increased relatively steadily since the first injections conducted in Phase I, and furthermore rebounded past Phase II baseline concentrations. Vinyl chloride has also increased throughout both phases of the EAB pilot studies. Freon 113 concentrations did not change substantially in this well during Phase II and are below action levels. The TOC retention time was 60 days and sulfate reducing conditions did not decrease to the desired 20 mg/L level. There is also an indication that iron reducing conditions were not reached, which is a precursor

to other electron acceptors such as sulfate. This indicates not enough substrate was available to initiate reducing conditions that sustain anaerobic treatment, causing incomplete degradation pathways. S140A is located near S141A, which is suspected to be impacted by the 440 Wolfe sump and nearby trenches. It is possible that this nearby well is also subject to influence by hydraulic conditions and should be considered for design modifications. It should also be noted that the PAIP tool was used to deliver the injection solution at INJ-8 which cause the sustained pressure to dip slightly to 150 PSI.

VOC concentrations in S146A rebounded or ultimately increased to above baseline levels. Sulfate reducing conditions were achieved but also rebounded. Methane production above the target was short-lived at 30 days. Ethene decreased at this well, and the rebounding and lack of methane and ethene generation indicates reductive dechlorination was limited. Freon 113 was initially reduced but rebounded in the third and fourth quarters quarter to reach 66,100 µg/L. Freon 113 inhibits reductive dechlorination by DHC (specifically *Dehalococcoides mccartyi*) in a concentration-dependent manner, causing cis-DCE stalls (Im J, 2019). In addition, the TOC retention time at this well was two quarters, another line of evidence hindering anaerobic treatment. The injection delivery tool used at nearby INJ-3 was the PAIP instead of the TDIP used at other injection locations. Using this tool, sustained pressures and flowrates for INJ-3 were limited at 70–100 PSI and 3.8 – 20.2 gpm with periodic tool clogging. Additional substrate will be needed in the area of this well to continue degradation, and it is recommended that the TDIP be used instead of the PAIP to ensure adequate injectate distribution. Addressing Freon 113 concentrations is also recommended.

S158A is a newly installed well located on the south end of the Phase II treatability study area. It was originally planned as an upgradient well, however the baseline TCE concentration of 8,100 µg/L extended the known horizontal extent of the plume southward (note that the concentration was qualified by the lab for exceeding the calibration range). After injections at nearby INJ-9, TCE

was reduced by 99.9% to <10 µg/L. ~~Cis-DCE peaked after injections, stabilizing at 22,000 µg/L for 90 days before decreasing to 44 µg/L in the third quarter and finally rebounding in~~ ~~Cis-DCE also decreased an order of magnitude however rebounded in the second~~ ~~fourth quarter.~~ Vinyl chloride followed a similar trend of decreasing in the third quarter and rebounding in the fourth quarter, ~~on the other hand, increased to above baseline concentrations by the end of the performance monitoring period.~~ The TOC retention time in this well is four quarters and contained 210 mg/L TOC at the time of the final sampling event, substantially above the recommended amount. Sulfate reducing conditions persisted through the performance monitoring period. The DHC microbial population was high, and gases were generated from fermentation and microbial activity as expected. Thus all signs point to an environment that sustains dechlorination, however monitoring VOC data does not indicate a degradation pathway is complete. Freon 113 was reduced to 79 µg/L from a baseline of 1,500 µg/L then rebounded in the fourth quarter. ~~Because TOC concentrations are substantial, further monitoring is recommended in this well to understand whether rebounds persist.~~

7 Conclusions

Performance parameters monitored throughout the study were evaluated against the Test Goals identified in Section 4.1 of the Work Plan. Work Plan Test Goals are identified in italics below. Findings are described following each Test Goal.

- ◇ *Improve the monitoring network by adding three additional monitoring wells in the treatability study area for baseline and progress monitoring; one additional well at the upgradient end of the treatability study area, and two additional wells at the downgradient end of the treatability study area.*

As seen in Figures 2 and 5, ~~w~~Well S158A was installed in the upgradient zone of the treatability study area, within the ROI of INJ-9. Wells S159A and S160A were installed in the downgradient zone of the treatability area in the ROI of INJ-7 and INJ-4, respectively.

Details of the monitoring well installation was discussed in the Injection Completion Report (Locus Technologies, 2021). In addition, three ad-hoc grab groundwater samples were collected immediately following injection (TW-1, TW-2, TW-3) and analyzed for VOCs to characterize the horizontal extent of the source area further. These wells were included in the baseline and post-injection (progress) monitoring as discussed in Section 4.2.3. Results from these new Phase II wells and of the expanded monitoring network are included in Section 4.5.

- ◇ *Collect injection pressure data at varying flow rates to refine injection procedures for future full-scale implementation.*

The collection of pressure and flowrate data provided useful information on effectiveness of direct push injection tooling, sustainable delivery rates, and site-specific fluid acceptance capacity. Overall, the TDIP tooling provided flexibility in the field for delivering the reagent at various pressures and flow rates. General injection flowrates of up to 26 gpm were achieved delivery rates were at sustained pressures of at 170 PSI across the injection column, and at flow rates of up to 26 gpm. Similar rates were observed for the delivery of loading volumes of up to 50% above design value. No daylighting or indication of fracturing was observed with the implemented injection techniques.

- ◇ *Gauge water levels surrounding injection points to measure the radius of influence (ROI) of the injection.*

Water levels were measured continuously as injections were conducted in the treatability area. These water levels were then graphed to visualize the impact of injection and determine the actual ROI, as discussed in Section 4.2.2. An ROI of 20 feet or greater was measured for ten out of twelve injections. The average ROI was estimated at 31-33 feet, based on qualifiable data (see Section 4.2.3). However, due to the extended injection activity period, in relation to Phase I study, a ROI greater than 20 feet may have been influenced by hydraulic disturbances resulting from the lateral displacement of resident

~~groundwater groundwater larger volumes.~~ Therefore, a ROI of 20–30 feet should be retained for future implementations.

- ◇ *Increase carbon availability across the study area to decrease electron acceptor profile, mitigate VOC rebounds, and support the repopulation of inoculated microbial cultures.*

Carbon availability varied across the reactive zone, shown by the TOC retention times in Figure ~~665~~. Wells S159A, S158A and S138A, which experienced the longest TOC retention times, may benefit from additional performance monitoring to evaluate the degree to which VOC rebounding will occur and the longevity of the repopulated DHC. In other areas of the reactive zone, additional carbon may be necessary to avoid rebounds, competition from other electron acceptors, and promote microbial growth.

The injection of SRS–SD resulted in a TOC increase from 1.8 mg/L to an average of 120 mg/L by end of second week of injections. Average concentration gradually decreased following this period and up to 77% ~~(28 mg/L)~~ by second quarter ~~(28 mg/L)~~. Overall, TOC retention rates suggest an increase in injection frequency or dosing concentration may be required to maintain target TOC across the reactive zone. However, the poor retention identified at specific locations may attributed to the effects of existing preferential pathways and high utilization rate for biotic degradation.

- ◇ *Increase Dehalococcoides (DHC) populations where populations have declined below the target of 1×10^6 cells/L (1×10^3 cells/mL) based on third quarter monitoring: S146A and S140A.*

Phase II injections successfully repopulated DHC at wells S146A and S140A, which remained above the screening criterion through the entirety of the Phase II monitoring period. The Phase II evaluation used a more conservative screening threshold ($>1 \times 10^4$ cells/mL DHC), recommended by Microbial Insights and recent studies. ~~After Phase II injections,~~ DHC populations surpassed 1×10^4 cells/mL in the reactive zone (confirmed during the Phase II 90-day monitoring event), except for well S160A which ~~barely~~

narrowly met the DHC target. By the third quarter, wells S159A and S160A decreased to below the screening criterion, and in the fourth quarter, with fourth quarter DHC populations were of 2×10^3 cells/mL and 4.7×10^3 cells/mL, respectively. This drop in population decline did not seem to have minimal effect on the performance at S159A based on the VOC concentrations; however, the low DHC populations compounded with low TOC at S160A indicates not enough injection solution was present in the well.

- ◇ *Implement a gridded injection, expanding reactive zone to reduce the effects of boundary conditions (the effects of untreated areas on treated areas) and migration of VOCs to downgradient areas.*

Twelve injections were planned in a triangular grid with 20 ft ROIs. The planned triangular grid is seen in Figure 4 of the Work Plan (Locus Technologies, 2020). After field verifications and discussions with the EPA, three planned injections (INJ-10, INJ-9, and INJ-6) were moved due to field constraints (see more details in the Injection Completion Report) which resulted in a deviation from the originally planned triangle grid. Figure 5 shows the final locations of the injections with the estimated ROI of 20 ft. Injections circles are adjacent to each other in most areas, however when the average actual ROI of 31–33 feet is incorporated, the injections overlap. The overlapping of injections helps reduce the effects of boundary conditions. Monitoring locations inside the reactive zone were sampled throughout the duration of Phase II study to further evaluate the boundary conditions. Downgradient wells S025A and S088A were monitored for adverse groundwater impacts and migration of VOCs. No adverse groundwater impacts were detected at downgradient wells as discussed in Section 4.11.

- ◇ *Implement a gridded injection based on a 20-foot ROI, verified with field observations such as water levels or appearance.*

As previously discussed, twelve injections were planned in a triangular grid with 20 ft ROIs; however, field constraints caused some of the locations to move resulting in three injections to the east, west, and south to deviate from the 20-foot ROI grid. ~~The~~ However, actual ROIs were greater and the average ROI was 31–33 feet as verified with water levels and discussed in Section 4.2.3. ~~4.2.24.3.~~

- ◇ *Determine the effectiveness of SRS-SD and TSI-DC bioaugmentation culture at promoting anaerobic degradation of chlorinated ethenes and Freon 113 at S140A and S141A.*

~~The injection solution of Phase II injections~~ SRS-SD and TSI-DC clearly promoted anaerobic degradation of chlorinated ethenes in the high-TCE and low-TCE wells, demonstrated by fluctuating VOC concentrations and the sharp decline of TCE in the reactive zone, refer to Appendix H plots. At the mid-range TCE wells in the northwest of the reactive zone, particularly S141A and S160A, the TOC retention time was very short (approximately 1 week), and reductive dechlorination of VOCs was less apparent. Overall, Freon 113 decreased at the majority of wells in the reactive zone, and Freon 113 concentrations were below the action level of 1,200 µg/L at all wells in the fourth quarter of Phase II, except for S146A.

- ◇ *Refine in situ remedial parameters for full-scale implementation.*

TOC retention times and EAB performance were affected by the hydraulic gradient and the existence of high permeability zones within the Phase II treatability study area. Thus, in situ parameters could not be fully refined and a modification of the design is recommended to accommodate these hydraulic influences. However, assuming direct push injections are used again, ROI and delivery techniques evaluations resulted in a recommendation of the TDIP tool over the PAIP. Phase II sustained pressures of 170 PSI did not cause daylighting whereas pressures below that did not result in adequate substrate distribution. Daylighting occurred above this pressure in Phase I, thus it recommended to continuing applying a pressure of around 170 PSI in the future. Using

the Phase II pressure, an average ROI of ~~31~~33 feet was observed, however the use of a 20-foot ROI is recommended due to potential displacements (see Section 4.2.3).

- ◇ *Demonstrate that injection of this substrate would not create unintended adverse impacts to groundwater.*

Manganese and arsenic increased in the reactive zone as a result of the reducing conditions caused by the EAB injections. Monitoring of downgradient wells however, showed that elevated manganese and arsenic were not found outside the reactive zone throughout the performance monitoring period. Therefore, unintended adverse impacts to groundwater were not encountered. Further details can be found in Section 4.1.1.

8 Recommendations

The study findings have indicated that a single injection of SRS-SD and TSI-DC was effective in promoting anaerobic biodegradation of VOCs at limited locations. However, the majority of the treatment area did not complete the degradation pathway due to limited TOC (carbon availability). Thus, source area treatment should continue, and the following recommendations should be implemented in the future remedy design:

- ◇ Conduct an additional pilot, Phase III, in the treatability study area for continued source treatment, and expand the treatment area to areas where VOCs persist. Because post-injection monitoring of Phase II is still ongoing, it is recommended to develop the work plan after the two-year monitoring event (scheduled for Q4 2022) and to consider the data from that event in the design of Phase III.
- ◇ During Phase II grab sampling, the lateral extent of the plume was discovered to reach further south. The monitoring network should be expanded to include more wells on the south side of the reactive zone and potentially more injections if baseline sampling of the new wells provides new information on the distribution of concentrations.

- ◇ Increase carbon availability across study area to decrease electron acceptor profile, mitigate VOC rebounds, and support the repopulation of inoculated microbial cultures. Based solely on TOC data, the results suggest an increase in injection frequency or dosing concentration may be required for a 12 month design cycle. The SRS-SD vendor Terra Systems has recommended a 12 month to 3 year design cycle.
- ◇ Observed delivery rates and TDIP tooling are recommended for future implementations, if other delivery parameters (i.e. injection depth, volumes, amendment material, etc.) remain the same.
- ◇ For further expansions of the EAB treatment area, implement a gridded injection based on a 20 to 30-foot radius of influence. Ensure the injections can be monitored adequately from all available monitoring wells or adding new wells if necessary.
- ◇ Conduct additional EAB performance groundwater monitoring at S138A and S158A to assess additional degradation by remaining TOC.
- ◇ The functional genes VCR and BVC do not appear to accurately reflect the site conditions and are not recommended to be used in the future as indicator parameters.
- ◇ Attempt to reduce elevated reported limits to enable comparison with performance indicators.
- ◇ Evaluate the physical well condition at S138A due to observed oscillations during injection water level gauging.
- ◇ Address Freon 113 concentrations at S146A that may be contributing to rebounding.
- ◇ Further refine in situ remedial parameters for full-scale implementation.
- ◇ Refine ROI of reagents by conducting tracer studies or similar studies.
- ◇ Based on the velocity investigation, modify the design to account for hydraulic conditions caused by extraction wells, sump, and potential preferential pathways in the treatability area. Modifications may include targeting zones within the A-aquifer by adjusting delivery techniques or the incorporation of recirculation techniques. A less viscous substrate may

be needed for recirculation design which would require more treatment studies. Modifications could also include the incorporation of secondary treatment technologies such reactive barriers or phytotechnologies, recirculation techniques. Phytotechnologies have been demonstrated to perform successfully at a nearby site with similar characteristics. The degradation mechanism (aerobic vs anaerobic) would need to be considered when considering its feasibility. A site visit is planned for assessing the feasibility further.

- ◇ Site-specific hydrogeologic conditions may also need further investigation if needed for the basis of design and targeted treatment. Injection back pressures could be evaluated to gauge groundwater transmissivity and areas of resistance. It is more desirable to target injections in clay lenses, reflected by higher back pressures rather than lower pressure depths that indicate higher groundwater transmissivity or potential for substrate loss. In addition, a membrane interface probe could be incorporated in the next design to characterize the extent of the VOC and identify migration pathways.
- ◇ Consider expanding treatment to the area north of the current treatability area, at 815 Stewart Drive. A separate work plan for this area should be developed with information from the Phase III pilot.

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TABLES



FIGURES



APPENDIX A

FIELD LOGS: WELL CONSTRUCTION, INJECTATE DELIVERY AND FIELD OBSERVATIONS

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APPENDIX B

INJECTION PERIOD GROUDNWATER LEVEL PLOTS



APPENDIX C

POST-INJECTION MONITORING LOGS



APPENDIX D

POST-INJECTION LABORATORY ANALYSIS REPORTS

(EUROFINS TEST AMERICA, PACE ANALYTICAL, ENTHALPY AND MICROBIAL INSIGHTS)



APPENDIX E

SOIL VAPOR METHANE MONITORING LOGS

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APPENDIX F

SOIL VAPOR LABORATORY ANALYSIS REPORTS

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APPENDIX G

QA/QC RESULTS ANALYSIS



APPENDIX H

CONCENTRATION TRENDS PLOTS



APPENDIX I

ADDITIONAL GROUNDWATER VELOCITY INVESTIGATION WELL DATA LOGS